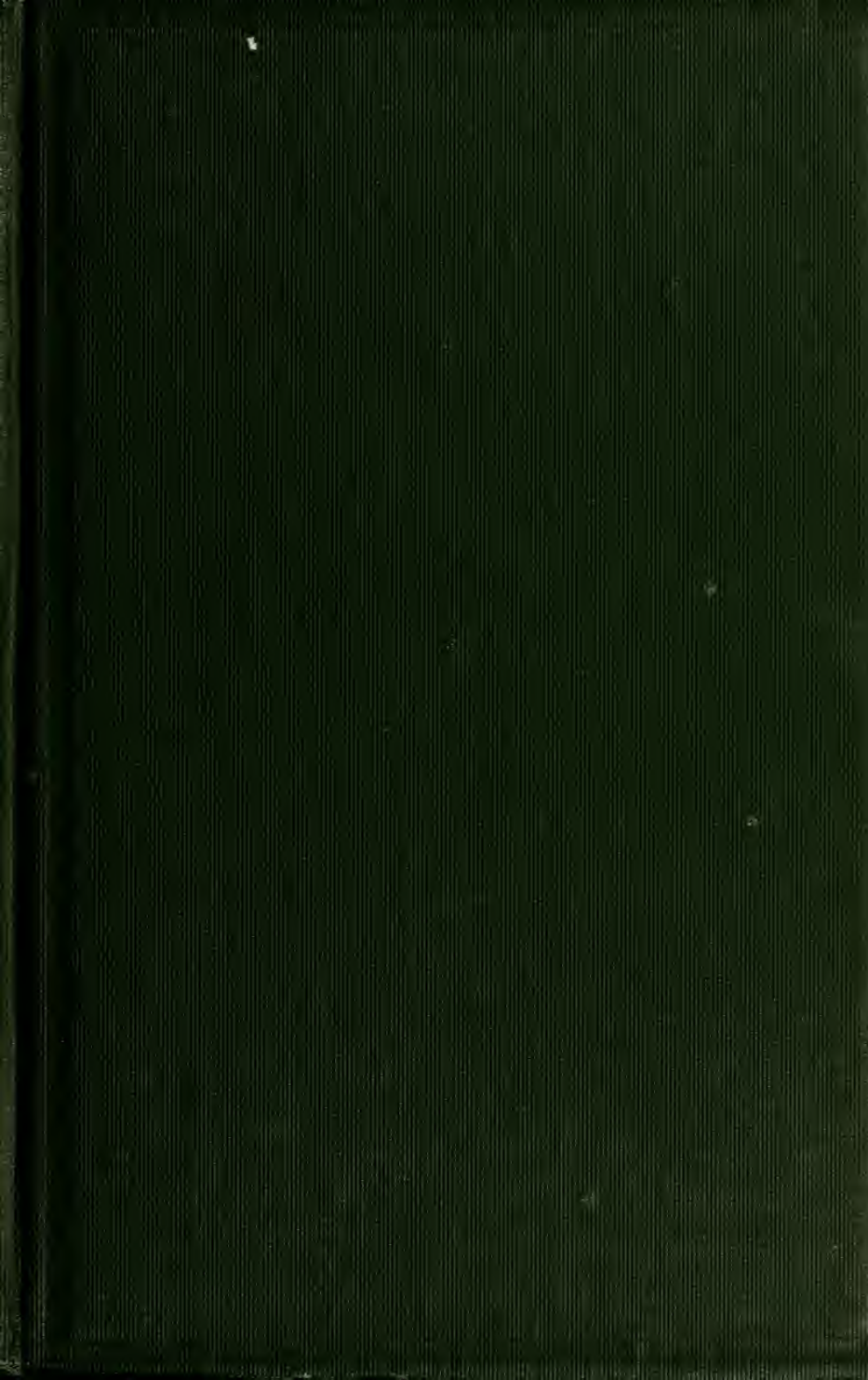
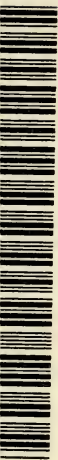






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PHYSICAL SCIENCE



NEWTON
Qui genus humanum ingenio superavit.

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THE RECENT DEVELOPMENT OF PHYSICAL SCIENCE

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PHILADELPHIA
P. BLAKISTON'S SON & CO.
1012 WALNUT STREET

<i>First Edition</i>	.	.	.	.	<i>August 1904</i>
<i>Second Edition</i>	.	.	.	.	<i>September 1904</i>
<i>Third Edition</i>	.	.	.	.	<i>December 1904</i>
<i>Fourth Edition</i>	.	.	.	.	<i>November 1909</i>
<i>Fifth Edition</i>	.	.	.	.	<i>August 1924</i>

PREFACE TO THE FIRST EDITION

IN recent years we have witnessed a great development of physical science. The different sections into which natural knowledge is, for the sake of convenience, divided, have grown each within its own domain; and, moreover, have shown increasing signs of extending beyond the boundaries arbitrarily traced between them. The methods of physics, in the restricted sense of that word, are being more and more applied to chemical and biological problems, while many questions in physics can only be investigated by those with mathematical or chemical training.

Thus it happens that an acquaintance with the knowledge newly acquired in one department of science is necessary for the study of another; indeed, the phenomena which need for their interpretation the methods of two branches of science have proved often the most fruitful field of inquiry.

For reasons such as these it has been thought possible that a short account of some of the important investigations now being carried on in the physical laboratories of the world might prove useful to students of science in general; while it is hoped that, by treating the subject as far as possible without technical language, the book may also appeal to those

who, with little definite scientific training, are interested in the more important conclusions of scientific thought.

The writer has been fortunate in his surroundings, where the knowledge and insight of one worker are placed freely and ungrudgingly at the service of another in the day of his need. In the present undertaking he records gratefully the help of several friends who have read the proof sheets of the parts dealing with subjects with which their names are closely associated. Mr F. H. Neville criticised the chapter on The Philosophical Basis of Physical Science, and that on Fusion and Solidification. Lord Berkeley read the account of The Problems of Solution. Professor J. J. Thomson saw the manuscript of the original article on which is founded the chapters on Conduction of Electricity through Gases and Radio-Activity. Professor Larmor revised the account of Atoms and *Æther*, while Mr H. F. Newall read the chapter on Astro-Physics. For this assistance the writer expresses his cordial gratitude. He wishes especially to thank his wife for continual correction both of the manuscript and of the proof sheets.

The editor of the *Quarterly Review* has kindly allowed use to be made of the article on Matter and Electricity which appeared in January 1904. Professor George E. Hale was good enough to permit some of his photographs of the sun to be reproduced, while, for other illustrations, acknowledgments are due to the Royal Society, to Mr Heycock and Mr Neville, to Mr J. A. Ewing, and to Mr G. T. Beilby. Lord Kelvin kindly sent a signed portrait, and

Professor J. J. Thomson allowed the use of a reproduction of Mr Arthur Hacker's admirable painting, which now hangs in the Cavendish Laboratory.

In spite of the generous help he has received, the author is sadly conscious of the difficulty of his task. Although the development of physical science is one of the most powerful activities of our time, a knowledge of its aims, methods, and results has not yet been recognised as a necessary part of an English liberal education. To give a popular exposition of results, especially when there is an obvious practical application, is easy ; to enable a non-scientific mind to follow and appreciate the methods by which the results are reached is supremely difficult. But in science methods are usually more important than results, while a superficial acquaintance with results without an underlying knowledge of method is useless, or worse than useless.

In the possibility of treating the wider and deeper generalisations of natural science as fit subject-matter for current thought and literature, the writer has a profound belief. Whether the failure to secure such treatment has been due to lack of adequate exposition, or to some radical defect in the training of the nation, is a difficult and grave problem ; but, until the point of view has been altered, it is perhaps hopeless to look for a proper understanding of the scientific spirit and of scientific method even among the more educated portion of the community. For the present, the man of science must perforce occupy a more technical and isolated position than the student of history or the lover of art. From

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the point of view of the man of science, to break down this isolation would be, at best, but sorry kindness; but, from a wider point of view, for the good of the nation and of mankind, a more general acceptance of a share in the impersonal open-minded search for truth, which is the essence of science, is ardently to be desired.

With some such thoughts as these, the writer sends forth the following pages.

CAMBRIDGE, *25th June* 1904.

PREFACE TO THE SECOND EDITION

THE need for a reprint of this book, coming as it does within a few weeks of publication, must be set down in part to the exceptional interest in the problems with which it deals that has been aroused by Mr Balfour's Presidential Address to the British Association.

For, when attention has been drawn to the new theory of matter—to "the most far-reaching speculation about the physical universe which has ever claimed experimental support"—a state of mind is created that, in thoughtful men, will not rest satisfied without some effort to understand the basis of the speculation, and to weigh the evidence which can be arraigned in its favour. Truly, the new theory is concerned, not "about things remote or abstract, things transcendental or divine, but about what men see and handle, about those 'plain matters of fact' among which common-sense daily moves with its most confident step and most self-satisfied smile."

The importance of the position now gained for the survey of the material universe lies in the unity of conception it discloses and the resulting simplification of detail. Either instinctively, or as the unconscious result of experience, the mind of man naturally grasps at any plan thus to reduce

and consolidate the questions which beset him in his journeyings through time and space. To the philosophic import of this mental attitude Mr Balfour has done well to call attention in words that he kindly allows the writer to reproduce :—

“ Now whether the main outlines of the world-picture which I have just imperfectly presented to you be destined to survive, or whether in their turn they are to be obliterated by some new drawing on the scientific palimpsest, all will, I think, admit that so bold an attempt to unify physical nature excites feelings of the most acute intellectual gratification. The satisfaction it gives is almost æsthetic in its intensity and quality. We feel the same sort of pleasurable shock as when from the crest of some melancholy pass we first see far below us the sudden glories of plain, river, and mountain. Whether this vehement sentiment in favour of a simple universe has any theoretical justification, I will not venture to pronounce. There is no *a priori* reason that I know of for expecting that the material world should be a modification of a single medium, rather than a composite structure built out of sixty or seventy elementary substances, eternal and eternally different. Why, then, should we feel content with the first hypothesis and not with the second? Yet so it is. Men of science have always been restive under the multiplication of entities. They have eagerly noted any sign that the chemical atom was composite, and that the different chemical elements had a common origin. Nor for my part do I think such instincts should be ignored. . . . These obscure intima-

tions about the nature of reality deserve, I think, more attention than has yet been given to them. That they exist is certain ; that they modify the indifferent impartiality of pure empiricism can hardly be denied."

The principle of simplicity lies at the base of all our explanations of phenomena, and Mr Balfour's address will do much to lead to a clearer recognition of its importance.

Advantage has been taken of this opportunity to correct a few verbal errors which appeared in the first edition of the book. The writer's thanks are due to several correspondents, some of them known to him personally and some not, who were good enough to send notes of these errors.

Certain additions, descriptive of work published within the last few months, have been made ; and in places the treatment has been modified in order to make the meaning clearer. In this task the writer acknowledges gratefully the help of his friend, Mr Stanley Leathes.

22nd September 1904.

THIRD EDITION

LITTLE more than verbal changes have been made in transforming the second into the third edition.

10th November 1904.

FOURTH EDITION

IN the four years which have elapsed since the publication of the third edition of this book, physicists have developed further the subjects with which it deals, but no striking new branches of knowledge have appeared. Hence it is possible to re-issue the book, with some additions, but with no fundamental changes of plan.

18th January 1909.

FIFTH EDITION

THE fifteen years which have passed since the last edition of this book appeared have seen great advances in many of the subjects described therein, and two new discoveries of fundamental importance—the Principle of Relativity and the Quantum Theory.

It has been necessary, therefore, completely to revise the book; many sections have been re-written, and much new substance has been added, in the attempt to give a fair account of the latest development of physical science.

22nd June 1924.

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PHYSICAL SCIENCE

CHAPTER I

INTRODUCTION

Not clinging to some ancient saw ;
Not mastered by some modern term ;
Not swift nor slow to change, but firm :
And in its season bring the law.

—TENNYSON.

IN the early years of the twentieth century, when this book was first published, physical science was developing mainly in two directions. Although these movements were contemporaneous, it is interesting to note that the methods used by the two schools of research were, to some extent, the expression of opposite tendencies.

On the one hand, we traced the growth of the study of the conditions in which all physical and chemical change in a system must cease—the conditions of physical and chemical equilibrium. This growth was due to the thermodynamic methods founded chiefly on the great work of the late Willard Gibbs, of Yale University in the United States. On the other hand, our knowledge of the mode of the conduction of electricity through gases was extended, mainly by the efforts of Sir Joseph John Thomson, Professor of Experimental Physics at Cambridge, and now Master of Trinity, and of the band of

workers trained by him and by his pupil and colleague Sir Ernest Rutherford, in the Cavendish Laboratory. Students from almost all civilised countries have come to Cambridge as to the centre of this branch of physical research, and many of them are now carrying forward their investigations elsewhere, by methods learnt in the University of Newton, Clerk-Maxwell, and Stokes.

When we again take up the story twenty years later, we see a marvellous increase in both these branches of knowledge. In thermodynamics much progress has been made by following principles already laid down, and applying them in new directions, especially in the subject of physical chemistry.

On the other hand, the study of the conduction of electricity through gases and the allied domain of radio-activity has attracted most of the work of experimental physicists. It has led to an unprecedented output of new knowledge and an amazing new insight into the secrets of atomic structure.

Moreover, two fresh subjects of inquiry have appeared. One of these depends both on thermodynamics and on atomic conceptions. The examination of the known facts of optical spectra had led Planck in 1901 to the view that radiation was emitted only in definite units, the constant unit being not energy but the product of energy and time—a quantity now called “action.”

This quantum theory was applied by Einstein in 1907 to explain the specific heat of solids, and by Bohr in 1913 to give a new picture of the

atom. In both these applications it has been very successful, but it involves the abandonment in problems of radiation and atomic structure of hitherto accepted dynamical principles.

Again, the theory of relativity, founded by Einstein and Minkowski, leads to another revolution in scientific thought. The ideas of absolute space and absolute time are held by this new view to be unwarranted though perhaps natural figments of the imagination. If we keep to the only space and time we really know, they can be but space and time as recorded by some observer; they will not, it appears, be the same for all observers; they are relative and not absolute. The real unity is a complex of both, and this space-time is absolute and not relative. Strange to say, this theory, as followed by Einstein, has led to a new outlook on the agelong problem of gravitation. The motion of the planets, the weight of a stone, may, it seems, be due to something we must represent as a curvature of space-time rather than to the now familiar but ever mysterious gravitational attraction of Newton.

As we shall see in the following pages, the chief work of modern experimental physicists is undertaken and interpreted by the aid of atomic and molecular conceptions. The theory of the conduction of electricity through liquids, based originally on the work of Faraday, and slowly matured by Hittorf, Kohlrausch, Arrhenius, and many others, had accustomed our minds to the conception of electric conduction by means of the motion of charged particles, called by Faraday "ions"—the travellers. Each ion consists of an

atom, or group of atoms, of the substance in solution, associated with a positive or negative electric charge; it moves through the liquid under the action of an applied electric force, and gives up its charge to the electrode—that is, the terminal by which the current enters or leaves the liquid. The conduction, instead of being conceived as a river flowing uniformly, must figuratively be represented as taking place by the passage of discrete quantities of electricity; in much the same way as water is sometimes carried from a lake to a burning house by means of a chain of bucket-bearers.

By the application of similar conceptions, the passage of electricity through gases has received a convincing explanation. Differences appear, but the fundamental ideas are the same in the two branches of the science of electrolytic conduction. It is, however, in the newer side of the subject that the most striking results have been obtained. Electrolysis in liquids had suggested the conception of ultimate units of electricity—atoms of electricity, analogous to the atoms of matter. Gaseous conduction enabled these electric atoms to be isolated, separated from their attendant material atoms, and studied independently.

Great has been the revelation which followed. The isolated atoms of negative electricity—the electrons, as they have been named by Stoney—have been identified by the work of Thomson, Lorentz, and Larmor, with one of the physical bases of matter, with the corpuscles, or sub-atoms, by means of which, combined in varying numbers and in different arrangements with a more essential positive nucleus, are composed

the chemical atoms, for long taken as ultimate indivisible units.

Further light has been thrown on these dark places by the remarkable series of discoveries through which M. and Mme. Curie and other chemists gave us the radio-active elements such as radium, and the parallel series in which Rutherford and his fellow workers have interpreted their properties as due to the disintegration of their atoms, as, one after another, those atoms break down, and are transmuted into other substances.

Throughout these investigations we deal with atomic and molecular conceptions in an extreme form. We look even within the atom, and examine its internal structure; we trace the electrons flying round the nucleus of the atom, as we watch the planets swinging round the sun.

It is remarkable that, in the other branch of Physical Science, in which thermodynamic principles are used, the methods chiefly employed enabled us for a time to dispense altogether with atomic and molecular theories.

At the basis of the theory of physical and chemical equilibrium lies Lord Kelvin's great principle of the dissipation of energy. While the total amount of energy in an isolated system is unchanging and unchangeable, that energy is tending always to become less available for the performance of useful work. The availability of the energy tends continually to become less. It follows that permanent equilibrium can only be attained when the limit has been reached and the availability is a minimum. Such a theorem is independent of molecular hypotheses; in fact,

it expressly disclaims such hypotheses, for, as Maxwell showed, the chance collisions of the individual molecules in a gas will lead to differing molecular velocities, and to a concentration of energy in the fast-moving molecules. If we could follow the motions of the individual molecules, and separate the fast from the slow, we could use this energy. The principle of dissipation, therefore, only holds while we are obliged, as always as yet in practice, to deal with ordinary molecules statistically and in the aggregate.

The principles thus applied to isolated systems have been extended to the visible universe. Predictions have been made that ultimately the energy of the universe will become completely unavailable, and will settle down into the energy of heat, uniformly distributed. But this final sleep of the universe depends on the assumptions that the universe is an isolated system, finite in extent, and that no process of molecular concentration of energy, such as was imagined by Maxwell, is going on anywhere throughout the depths of time and space.

A more restricted, though more fruitful, application of the dissipation principle enabled Helmholtz, and, in a much more general manner, Willard Gibbs, to place on a firm footing the theory of non-isolated but isothermal systems—systems, that is, maintained at a uniform and constant temperature by the gain or loss of outside heat. The external work which such a system can perform, by means of a reversible change at constant temperature, tends to a minimum, and the system is in permanent equilibrium when, and when only, this available

or free energy, as it is called, becomes as small as possible. By this sole principle, Willard Gibbs developed the complete theory of chemical and physical equilibrium; as Sir Joseph Larmor says, his "monumental memoir made a clean sweep of the subject; and workers in the modern experimental science of physical chemistry have returned to it again and again to find their empirical principles forecasted in the light of pure theory, and to derive fresh inspiration for new departures."

Simultaneously with the development of experimental research along the several lines we have indicated, there has arisen afresh an interest in and inquiry into the philosophic basis on which is built the whole magnificent structure of modern science. How far is that basis secure? Are the conceptions of science life-like pictures of any fundamental reality behind the phenomena which alone our senses can apprehend? Such questions have occupied periodically the ablest minds of certain epochs of history, though in the attempts to find answers no such general consensus of opinion has been reached as we see within the building of science itself. Granted the security of the foundations, the edifice seems designed on a consistent plan, for the relations of its parts present themselves similarly to all minds competent to judge.

The philosophy of science is intimately connected with its history; and interest was stimulated afresh in the philosophical problems involved in physical conceptions by the publication of Mach's great work on the Science and History of Mechanics. To many that book put new life into the subject treated in its pages, and it has

led to a more careful consideration of the fundamental conceptions of natural science in general by experimental and mathematical physicists.

In more recent years fundamental changes of outlook have been made by the recondite researches of Bertrand Russell and A. N. Whitehead, and the less mathematical writings of C. D. Broad.

In the following pages an attempt will be made first to consider the philosophic foundations of physics, and then to trace some of the more important developments of the experimental investigations for which the last few years have been remarkable.

The study of physical equilibrium—the equilibrium between different states or phases, solid, liquid, and gaseous, of the same substance—naturally opens with the consideration of the relations between the different states of pure chemical elements and compounds. Here, the most striking work is the liquefaction of air and hydrogen, with which the name of Dewar most prominently must be associated.

Next we turn to mixtures, and the fusion and solidification of solutions and alloys claim our attention. The microscopic analysis of metals, when elucidated by the theory of equilibrium, has had far-reaching influence on the applied arts of metallurgy.

Then are considered the problems of solution in general, without restriction to conditions of equilibrium. Now, for the first time, we come in contact with electrical phenomena; and the theory of ionic conduction throws light, not only

on the nature of electrolytic solutions, but on many physiological questions of vital interest.

A natural step leads from the conduction of electricity in liquids to its conduction in gases, and, on our stage, the ion is joined by the corpuscle or electron. The dream of the old philosophers of a common basis for matter is realised by experimental investigation.

Arising from these experiments and their interpretation comes the theory of radio-activity, the modern equivalent of the imagined transmutation of the mediæval alchemist. We see and measure the gradual disintegration of the chemical elements, and draw on the energy stored within the atoms themselves. Rutherford has even succeeded in inducing such changes artificially in some few elements.

The vibrations of electro-magnetic systems produce the æthereal waves now used in wireless telegraphy, and the vibrations of atomic systems give rise to light. Thus atoms must be related intimately to light, and light to electro-magnetic phenomena.

Our model of an atom must clearly explain not only the facts of radio-activity, but those of radiation also. If electrons radiate energy as they revolve in planetary orbits, they should, on ordinary dynamical principles, move faster and faster and circle nearer and nearer to the nucleus. Hence a number of atoms should emit waves of all possible periods of vibration and wave lengths. But this deduction is inconsistent with the well-known bright line spectra of many elements, spectra showing vibration in one or a few definite periods only. This was the origin of

Planck's theory that radiation can leave an atom only in definite units or quanta—a theory which, as we shall see, explains bright line spectra, but seems to be inexplicable on the principles of classical mechanics.

Finally, we pass to the bearing of all this new knowledge on cosmical problems. Physics is rapidly annexing the domain of astronomy, as it has already invaded the realms of chemistry and biology. By the aid of the spectroscope we examine the chemical nature of the sun and stars, we measure the rates of their motions and revolutions, and obtain data from which we may speculate about their origin, development, and decay. And the principle of relativity teaches that time and space are relative to ourselves, and their mysteries not unconnected with the mystery of the human mind. From the internal structure of the atom to the majestic progress of the suns, the investigations of Physical Science are surely and continuously gaining new knowledge for mankind.

We scatter the mists that enclose us,
Till the seas are ours and the lands,
Till the quivering æther knows us,
And carries our quick commands.
From the blaze of the sun's bright glory
We sift each ray of light,
We steal from the stars their story
Across the dark spaces of night.

But beyond the bright search-lights of science,
Out of sight of the windows of sense,
Old riddles still bid us defiance,
Old questions of Why and of Whence.
There fail all sure means of trial,
There end all the pathways we've trod,
Where man, by belief or denial,
Is weaving the purpose of God.

CHAPTER II

THE PHILOSOPHICAL BASIS OF PHYSICAL SCIENCE

Homo, naturæ minister et interpres, tantum facit et intelligit quantum de naturæ ordine re vel mente observaverit. . . . Natura enim non nisi parendo vincitur. . . .

—BACON, *Novum Organum*.

THE mind of man, learning consciously and unconsciously lessons of experience, gradually constructs a mental image of its surroundings—as the mariner draws a chart of strange coasts to guide him in future voyages, and to enable those that follow after him to sail the same seas with ease and safety. The chart may be drawn to scale; it may be consistent with itself and serve its purpose—but it only represents the earth's surface in one limited and conventional manner; it does not give a life-like picture of the original in the same sense as does a photograph or a painting. So it is with the ideas that our minds conceive of the world around us, and with the model of that world which our minds construct. And this analogy may serve to interpret to us our attitude towards the conception that the human race has formed of the world we live in. If the model be consistent, if the various parts and aspects of it do not fail to correspond with each other, it serves the double purpose of introducing order into what would otherwise be mental confusion, and of

helping us to make systematic use of the resources of Nature.

Confronted with the mystery of the Universe, we are driven to ask if the model our minds have framed at all corresponds with the reality; if, indeed, there be any reality behind the image. Such a question is a proper study of philosophy, but need not necessarily be answered for the model to be made or used. The whole problem mankind has to face undoubtedly includes this fundamental question of the ultimate nature of reality, which would enter into a complete explanation of every fact, even of those which we regard as the simplest. This aspect of the problem is the subject of that branch of philosophy usually known as Metaphysics. But, if we confine our attention to the phenomena which our senses apprehend, and, thus restricting our inquiry, examine our mental picture of Nature and the relation of its parts to each other, testing their correspondence or want of correspondence, we are studying Natural Science. The limitation indicated has not always been observed, and the name of Natural Philosophy survives to remind us that Natural Science is but one part of the whole of conceivable knowledge.

Philosophy may be divided into two departments. They are called by Broad Critical Philosophy, the analysis of our fundamental concepts and beliefs, and Speculative Philosophy, which takes over the results of science and of other modes of human experience, and, in the light of all the evidence, considers the nature and meaning of the Universe.

The problem of Speculative Philosophy is

of much greater difficulty than that of Critical Philosophy or of Natural Science. Hence, Natural Science has only begun to make rapid progress since its separation from Speculative Philosophy. Despite the closest attention of the acutest intellects since the age of Greece, no general consensus of opinion has been reached by metaphysicians. Materialism, Dualism, Idealism, inconsistent views of the nature of reality, are all of them still held by competent philosophers :

Myself when young did eagerly frequent
Doctor and saint, and heard great argument
About it and about : but evermore
Came out by the same door where in I went.

The slow and laborious methods of observation and experiment have been pursued from the earliest times for purposes of common life and technical industry. They were first considered philosophically though inadequately by Bacon, and by their help a firm ground has been obtained for the edifice of Natural Science. In contrast with the results of Speculative Philosophy or Metaphysics, a general consensus of scientific opinion upon fundamental points has been obtained. No physicist doubts the validity, within narrow limits of error, of relations established accurately by experiment, though the theories by which those relations are explained may be subject to periodic revision.

But observation and experiment can be directed only to the examination of our conceptions. In this way we gain materials for the construction and examination of the mind's model of reality; we do not touch reality itself. If this be doubted, we must reflect that we can

apprehend the results of experiment through our senses alone. Though, for instance, the galvanometer seems at first to supply us with a new electrical sense, on further thought we see that it merely translates the unknown into a language our sense of sight can appreciate, as a spot of light moves over a scale. It is possible that Philosophy may take into account knowledge which reaches us by means other than the senses. Intuitions, fundamental assumptions, mental processes generally, doubtless have an external aspect, and may be studied by the science of Psychophysics, but they may have also another aspect in their internal relations to consciousness. Here they can be examined by Psychology. But we can only study Nature through our senses—that is, we can only study the model of Nature that our senses enable our minds to construct; we cannot decide whether that model, consistent though it be, represents truly the real structure of Nature; whether, indeed, there be any Nature as an ultimate reality behind its phenomena.

In emphasising the essential distinction between Natural Science and Metaphysics, we must not suppose that the results of Natural Science have no metaphysical import. The possibility of putting together a consistent mental model of phenomena is a valid metaphysical argument in favour of the view that a consistent reality underlies those phenomena, and that the reality is represented with more or less faithfulness by the mental picture we have pieced together. Such an argument must carry great weight, and may, perhaps, be considered con-

clusive ; but it is a metaphysical argument, not one with which Natural Science is concerned directly. In framing and attempting to answer her own deeper questions, Metaphysics uses the results of Natural Science, as indeed of all other branches of inquiry. But this does not make Natural Science a branch of Metaphysics, or remove the essential difference between the subjects of the two studies.

The object of Natural Science, then, is to fit together a consistent and harmonious model which shall represent to our minds the phenomena which act on our senses. We need not fear that this limitation will lower the dignity or circumscribe unduly the extent of our inquiries. Whether we look inwards or outwards, the complexity of the phenomena seems boundless :

Boundless inward in the atom ; boundless outward in
the whole.

The more we learn, the more various and intricate are the new avenues of research which open before us. As has been well said, the larger grows the sphere of knowledge, the greater becomes its area of contact with the unknown.

So complex would be an entire mental picture of phenomena, that divisions of Natural Science have arisen, each of them tending more and more to demand the exclusive attention of the specialist. These divisions are purely arbitrary ; they have arisen partly from differences in methods of inquiry, partly from historical reasons. Moreover, they are variable, and are shifted from time to time according to the needs of each

department and the prevalent direction of inquiry, while new divisions may spring into existence.

The different sciences are not even parts of a whole; they are but different aspects of a whole, which essentially has nothing in it corresponding to the divisions we make; they are, so to speak, sections of our model of Nature in certain arbitrary planes, cut in directions to suit our convenience. Thus a nerve-impulse may be considered in a psychological aspect, a physiological aspect, or a physical aspect. Even these divisions may be sub-divided; the physics of the nerve-impulse may be studied first from the electrical side by investigating the electric currents that accompany it, and then from the mechanical side, by correlating the electrical currents with the movements of matter that simultaneously occur. No one of these aspects of the phenomenon is essentially more fundamental than any other, and the conviction at one time prevalent, and even now by no means uncommon, that a complete mechanical explanation of every phenomenon is possible and fundamental, seems merely an unphilosophical fallacy. Its origin is to be sought in the historical fact that the section known as mechanics was the earliest of the physical sciences, and that its methods and conclusions are fairly intelligible to the ordinary man, and, in their elements, essential to his daily life. The science of mechanics has been more fully developed from its experimental basis by the methods of mathematical analysis than any other branch of Natural Knowledge, and mankind has hence come to believe that it is essentially simpler

and nearer reality. But in truth it is no more fundamental than electricity, and, as we shall see in the following pages, there has been a tendency to conceive matter itself as an electrical manifestation. Indeed, the theory of relativity leads to the view that matter is a form of energy—perhaps but a property of a combined continuum of space and time.

Again, it is sometimes argued that mechanics is the fundamental science because its extension is universal, while that of physiology, for example, is not. The contraction of a muscle has clearly a mechanical aspect, while the fall of a stone to the earth has nothing to do with physiology. Even a thought, from one side purely a psychological phenomenon, may have a mechanical aspect if we could trace the physical changes in the brain which accompany it, whereas, it may be said, the expansion of steam in an engine has no psychological significance. Such considerations certainly indicate that the arbitrary plane cut through our solid model of the universe by mechanical science is cut in such a place that it traverses a large part of the model—a larger part, perhaps, than any other section which has yet been cut. It does not follow, however, that it cuts through the whole; still less that a plane section can represent fully a solid model. Thus the argument that, because of its wide extension, mechanics has some fundamental significance is seen to be a fallacy. It may be *prima inter pares* of the natural sciences, but nothing more. To go even further than this, as has sometimes been done, and to suppose that the ultimate nature of reality is the same essentially as our

idea of a single arbitrary section, cut through an imaginary model of it, seems only to need stating in these terms to be disbelieved.

The study of physics enables us to examine nature from a broader standpoint than that used by mechanics. But here again other aspects must be ignored. As Mach has well said, "Physical Science does not pretend to be a complete view of the world ; it simply claims that it is working towards such a complete view in the future. The highest philosophy of the scientific investigator is precisely this toleration of an incomplete conception of the world and the preference for it rather than for an apparently perfect but inadequate conception."

When the experimental study of nature was new, when man first caught a glimpse of order in the multiplicity of phenomena, such a view of the all-comprehending character of physical science seemed just. Let us again listen to Mach :—

"The French encyclopædists of the eighteenth century imagined they were not far from a final explanation of the world by physical and mechanical principles ; Laplace even conceived a mind competent to foretell the progress of nature for all eternity, if but the masses, their positions, and initial velocities were given. In the eighteenth century, this joyful over-estimation of the scope of the new physico-mechanical ideas is pardonable. Indeed, it is a refreshing, noble, and elevating spectacle ; and we can deeply sympathise with this expression of intellectual joy, so unique in history. But now, after a century has elapsed, after our judgment has grown more

sober, the world-conception of the encyclopædists appears to us as a mechanical mythology in contrast with the animistic mythology of the old religions. Both views contain undue and fantastical exaggerations of an incomplete perception. Careful physical inquiry will lead, however," to a more complete philosophy. "The direction in which this enlightenment is to be looked for, as the result of long and painstaking research, can of course only be surmised. To anticipate the result, or even to attempt to introduce it into any scientific investigation of to-day, would be mythology, not science."

Physical Science, then, the subject of the present work, is merely one aspect from which we may agree to look at the model of Nature that our minds construct. It ignores the biological standpoint, from which phenomena are regarded in their bearing on life; it ignores the psychological standpoint, from which they are studied in relation to mind. With these limitations, let us see what kind of model of Nature we are led to build.

From the complex mystery that is Nature the human mind singles out certain relations of parts of the whole to itself, and thus at once simplifies and formulates the problems, as it simplifies knowledge by the arbitrary division into such sections as physics, chemistry, and biology. The ideas of length and time may be regarded from this point of view as primary—length as the simplest form of space conception, time as a recognition of sequence in our states of consciousness.

One of the earliest advances in exact science was the power of counting and the resultant method of expressing quantities as numbers. In spite of its essential nature, the capacity for so doing is by no means innate; nor is it even yet properly developed among all the races inhabiting this globe. In order to measure quantities, it is necessary to choose or invent some unit, and then to count the number of times that unit is comprised in the quantity to be measured. In a civilised country the unit of length is taken as the length between two marks on a certain standard metallic bar. In England there is a standard yard, and in France a standard metre. In fact, both these units are arbitrarily selected for their convenience, though the original idea of the metre was derived from a connection with the supposed dimensions of the earth.

Like the unit of length, the unit of time is arbitrary, and ultimately rests on a measure of our sequence of consciousness. Again we have to choose some arbitrary unit, which, in this case, should always contain, under similar conditions, a similar amount of human consciousness. For purposes of the convenience of daily life the obvious unit to select is the day, while the sequence of the seasons suggests another equally arbitrary unit—the year. The exact relation between these two units can only be determined by careful astronomical observation. Wrong determination and consequent re-determination have led from time to time to necessary changes of calendar; while the partial adoption of these changes has resulted in the inconvenient differences of date in vogue among the various nations.

That the units of time cannot be regarded as essentially fixed and unalterable is clear when we remember that any friction on the earth, such as that of the tides, is slowly prolonging the day, while resistance to the bodily motion of the earth round the sun would gradually alter the length of the year. Such changes may be appreciable only after millions of years; but their possibility shows that our time-units are as arbitrary as are those of length.

But, even though our practical units of time and length are arbitrary, their statement assumes that there are such things as absolute time and space in which events take place. The principle of relativity has now taught us that time and length are always relative to some observer, and that only a continuum of space-time can be considered as absolute and independent. Nevertheless, our present scheme of science has been built up on these concepts now proved to be relative, and we may continue to use them as a matter of convenience.

From the conceptions of length and time, and the arbitrary units chosen to measure them, may be derived the more complex ideas required for a description of motion, and the derived units needed to investigate it quantitatively. Thus velocity is measured by the ratio of the number of units of length to the number of units of time, while acceleration, or the rate of change of velocity, is measured by the number of units of velocity gained or lost per unit of time. These relations are expressed by saying that the dimensions of the unit of velocity are L/T , while those of the unit of acceleration are v/T or L/T^2 .

With metaphysical theories of matter, Physical Science has no direct concern ; and mechanics, at any rate, deals only with matter as that conception, which, in our mental image of phenomena, is always associated with another and more definite conception, that of mass. We need not ask whether matter has any objective existence, or whether our conception of mass corresponds with any actual property possessed by a real thing-in-itself. Such inquiries are of great interest and importance ; but they are metaphysical inquiries, not those which the physicist, as physicist, must answer.

The conception of mass, as distinct from that of weight, may arise from the results of our daily experience. Let us suppose, for instance, that two fly-wheels of the same size, one of wood and the other of iron, were mounted on axles, and were free to revolve. When the wheels are set spinning, the weights do not come into play, for neither wheel is raised or lowered as a whole. Nevertheless, a great difference will be felt if we try to set the two wheels in motion suddenly. It takes either a much harder push or a much longer time to produce a certain velocity of rotation in the iron wheel than in the one made of wood, and, on the other hand, once moving, the iron wheel is much more difficult to stop. It is these results which lead us to say that the mass of the iron wheel is the greater.

The idea of mass first arises from the sense-perception of force ; but, to examine mass quantitatively, more definite observation is necessary. The mutual action of two bodies, as examined by experiment, is such that our description of

their relative motion becomes greatly simplified by assigning to each of them a certain relative number to express a quantity which we may term its relative mass. Let us make the two bodies, when free to move, act on each other in any way, excluding the possibility of rotation, for the sake of simplicity. Let us, for instance, connect them by means of a long, stretched elastic cord, and allow them to move each other. After the action has begun, we shall find that one body is, in general, moving faster than the other, and that the ratio of their accelerations is constant. The inverse ratio of these accelerations is the measure of the ratio between the masses of the two bodies; the body with the smaller mass is moved faster by the mutual action than is the body with the greater mass.

We now need only to choose some mass as our unit with which to compare other masses, and to prove experimentally that the mass of a body as thus defined is a constant quantity, to complete our preparations for using the conception of mass in our physical description of observed phenomena.

In all ordinary physical and chemical changes, mass is found to be constant. But, when a particle is travelling at speeds approaching that of light, its mass, as measured by an observer at rest, increases. Thus mass, like length and time, is not absolute; its value depends on its relation to an observer. But with this caution we may use the old concept of a constant mass with those of length and time as the basis of a system of physical units.

Experience shows us that we can generalise

the result of our experiment on the motion of the two bodies connected with each other by means of a string. We can assert that no body has an acceleration unless another body is acting on it. Thus, we cannot form a complete picture of the motion unless we consider both bodies. But it is often necessary to concentrate our attention on one of them, and it is then convenient to find some quantity which measures correctly the effect of the other body on the first. This quantity is not the acceleration, for that depends on the mass of the moving body, but it is the product of the mass and the acceleration, and is independent of both. This product records completely the mechanical effect of the second body; it may be taken as an accurate definition of that quantity, of which a rough measure is given by our sense-perception of force. Philosophically, force is the more fundamental concept, but for physics it may be defined as mass-acceleration, and instead of saying that one body is acted on by another, we may, if more convenient, say that it is acted on by a force. If a force moves its point of application, work is done, and the quantity of work is measured by the product of the force and the displacement in the direction of the force. The capacity for doing work is known as energy. A clear distinction is to be made between the ideas of force and energy.

Together with the conceptions of length, time, and mass, the conception of force also was employed by Newton in his development of mechanical theory. A simultaneous and parallel development of the science was led by Huygens, who used the conception which we now call

work or energy as a means of co-ordinating the phenomena, instead of stating them in terms of force as Newton did. Although it gave a more intimate insight into mechanical processes, Newton's method was perhaps less general than that of Huygens, which often enables us to pass directly from a knowledge of the initial to a prediction of the final state of a system, and to avoid the difficulties of tracing its intermediate operations. In the history of mechanical science, now one method and now the other has proved the more useful; and, in the wider field of physics, the two schools are still represented, on the one hand, by those who seek to trace the intimate processes of change by means of molecular theories, and, on the other, by those who rely on a more general presentment, which avoids such hypotheses by the use of the principles of thermodynamics.

By simple experiments, such as those described above, the relative masses of two reacting bodies may be measured by the constant inverse ratio of their accelerations. It follows that the product of the mass and the acceleration is the same for the two bodies. Thus the force which the first body exerts on the second is the same as the force which the second exerts on the first; or, as Newton expressed it, action and reaction are equal and opposite.

The conception of mass, in the present sense of the word, we owe to Newton: before his day no clear distinction was made between mass and weight. On the principle of relativity mass and weight are necessarily connected, but, as defined above, we cannot predict whether mass has any

relation to weight ; any discovery of a connection between them must be a matter of experiment.

Weight is the force which we must apply to a body to prevent it moving in its natural path towards the earth, the product of the mass and acceleration being the same for the earth as for the body. If the forces were equal, the accelerations towards the earth of two bodies would, by our definition of mass, be inversely proportional to their masses. By experiments on the acceleration, then, the forces may be determined. Now it was shown by Galileo that, if the resistance of the air be eliminated, bodies fall at the same rate to the earth ; that is, that the accelerations of all bodies to the earth are the same. It follows that the forces, that is, the weights of the bodies, must be proportional to the masses. Masses can thus be compared by weighing, and this method is much the most convenient in practice. Nevertheless, it must always be remembered clearly that the proportionality between mass and weight, and the consequent possibility of comparing masses by means of the balance, is not a relation which could be predicted *a priori* except by the recent and at present unfamiliar ideas of relativity, but one which historically has been established as the result of careful experimental investigation.

When we turn from mechanics to the other branches of physics, it is necessary, in the present state of knowledge, to use certain new fundamental conceptions, such as temperature and quantity of electricity, though it is probable that ultimately these quantities will be connected with the mechanical units. Again, in this place it

should be remarked that such a connection would not show that mechanics is necessarily the more fundamental science : it would be quite as correct, when the connection is established, to express mechanical quantities in terms of electricity or temperature.

This example leads us to state in a general form the immediate object of Physical Science. The physicist seeks to discover the relations between different phenomena, considered in one limited aspect, and to express those relations in a definite quantitative way. Our minds, led by the analogy with their own volitions, usually think of one of the related phenomena as the cause, and of the other as the effect. The physical equation which expresses the dependence of A on B , or, in symbols, $A = f(B)$, may equally well be written in the inverse form, by which B is asserted to be a function of A . In such cases, there is probably no philosophical distinction between cause and effect ; it is no more right to say that an increase of pressure produces a decrease of volume in a gas than to say that a decrease of volume produces an increase of pressure. The student merely discovers by experiment that the two phenomena accompany each other in every case investigated, and sums up the results of experience in conceptual language and in a shorthand form, in order to save the detailed investigation of each future individual case.

In these examples, the needlessness of the ideas of cause and effect will be fairly clear, whatever may be thought about their metaphysical importance. It is where the element of time is

involved that the idea of causation is most vivid. When one of the two related phenomena seems to follow the other, the mind instinctively identifies *post hoc* with *propter hoc*. The principle of relativity has shown that there is no absolute scale of time in which events may be placed in order. In some cases, one observer may say that A precedes B, while to another B happens first. But, even if a distinction between cause and effect is philosophically difficult, as a matter of convenience in language it is perhaps justified. When carefully examined, however, the difficulty of isolating the "cause" of any particular "effect" will be found to be insuperable. A long train of circumstances has preceded the phenomenon considered, and the phenomenon would not have appeared had any one of those circumstances been absent. Each or all of them might equally well have been called the "cause." Whether the idea of cause and effect represents a real distinction in the hypothetical world which our conceptions represent, remains, like the nature and existence of that world itself, an inquiry for the philosopher.

Physical Science, then, seeks to establish general rules which describe the sequence of phenomena in all cases. Underlying all such attempts is the belief that such an orderly sequence is invariably present, could it only be traced. This belief, which is the result of constant experience, is known as the principle of the Uniformity of Nature. In its absence no organised knowledge could be obtained, and any attempt to investigate phenomena would be perfectly useless. Unless, to use the conven-

tional language justified above as a matter of convenience, like causes always produce like effects in like circumstances, science, and indeed all organised knowledge, would be impossible.

When fitted into our mental picture, a generalised result of experience is known as a physical law, or, to change the form of a word and the size of two letters, as a Law of Nature. Many brave things have been written, and many capital letters expended in describing the Reign of Law. The laws of Nature, however, when the mode of their discovery is analysed, are seen to be merely the most convenient way of stating the results of experience in a form suitable for future reference. The word "law" used in this connection has had an unfortunate effect. It has imparted a kind of idea of moral obligation, which bids the phenomena "obey the law," and leads to the notion that, when we have traced a law, we have discovered the ultimate cause of a series of phenomena. Newton and Ohm did not first promulgate and then enforce the regulations which are associated with their names, though it is not only elementary students who may be heard saying that a stone falls to the ground "because of the law of gravitation." We must still ask why each particle of one body attracts each particle of another, even if there be a force between them proportional to the product of the masses divided by the square of the distance. We do not necessarily know why the electric current through a conductor varies as the applied electro-motive force, when we have discovered how these two quantities are connected.

The great change in the rate of progress of

Natural Science has occurred since men learned to concentrate their immediate attention on the question of *how* phenomena are related, and to cease, for the time at any rate, to ask *why* they appear. Before Galileo's day men sought to explain the fall of bodies to the earth by saying that "every body sought its natural place"—the place of heavy bodies being below, and that of light ones above. Galileo, exercising the true scientific spirit of restraint, set himself to determine by experiment *how* bodies fell. He thus discovered that the speed was proportional to the time of fall, and, by dropping bodies from the leaning tower of Pisa, showed that, contrary to the received doctrine of tendency to seek their natural place, heavy bodies fell no faster than light ones.

The natural laws of falling bodies were thus established, and the method of their discovery shows how such steps in knowledge are always made. In the first stage new phenomena are observed, or old phenomena are brought under accurate and quantitative measurement, probably by the light of tentative hypotheses. Here the virtues of patience, accuracy, incredulity, and conscientious elimination of personal bias are of chief account. The classical example is Kepler's life-study of the motions of the planets—a study which led to the establishment of general laws, such as that the planets move in ellipses having the sun in one focus.

But such laws alone are insufficient to satisfy our minds, which inevitably return to the question why such relations hold. The relations are misinterpreted and re-interpreted, until some Newton

with the touch of genius which often accompanies sober scientific insight and imagination—some one who is able to brush aside for a time the non-essential, and to rise above the confusion of detail—is inspired with a conception of order in the multiplicity of the phenomena: order to be seen when some simple principle is borne in mind, and is expressed in a formula, which, in terms of our conceptual shorthand, enables us to remember and to predict the sequence of phenomena. If the formula is expressed in terms of simple conceptions, already known and often used in other branches of knowledge, the mind at once looks on it as an “explanation” of the phenomena, though it is evident on further thought that the phenomena are no more fully understood than are the fundamental conceptions—mass, space, time, whatever they be—in which the “explanation” is expressed.

The next step consists in deducing new consequences of the hypothesis; and here the methods of mathematical analysis are usefully applied. The science of mathematics as such has nothing to do with natural phenomena. Like physical science it is concerned with ideal conceptions; but neither does it seek to gain those conceptions from an examination of Nature, nor to check their correspondence by the methods of experiment. Mathematics may borrow subject-matter from observational science, or may acquire by pure mental processes subject-matter, such as the geometry of four dimensional space, which may or may not have a counterpart in Nature. In either case, mathematics deals with the conceptions as such, and traces their results and the

relations between them by the methods of logic, with no necessary intention of elucidating the phenomena of Nature. Except when inventing new methods, the mathematician is a calculating machine. His conclusions are, or ought to be, contained implicitly in the premises he uses. He develops the premises, discovers their full meaning, and elaborates their consequences, in a way quite beyond the unaided power of thought, which, without the guiding rules and generalisations of mathematical analysis, would be lost in the maze of complications. But the mathematician lives in a purely conceptual sphere, and mathematics is but the higher development of symbolic logic.

Taking, then, a new-born hypothesis, its consequences are deduced by logical common-sense reasoning ; and, where such reasoning cannot see its way unaided, by the help of mathematical analysis. The results thus obtained are then used by the observer or experimenter, who tests by the use of old, or the determination of new data, the truth of the formula by every possible means. Its relations to other ascertained principles, its power of correlating hitherto unconnected phenomena, are examined in turn. From consideration of its significance, we gain suggestions for further observation, if possible for future experiment. Such experiments, undertaken with the express purpose in view, are probably better adapted to test the formula than the observations previously accumulated. If the concordance is complete as far as the accuracy of experiment can go, the formula becomes, in the then state of knowledge, an accepted theory. Whatever this means, such a generalisation will,

at all events, prove a useful working hypothesis, by the light of which research may be guided into promising paths. As the range of observation widens, and as the accuracy of the old observations is increased, the fate of the new theory hangs in the balance. The formula may, perhaps, still be confirmed, it may require modification, or it may have to be abandoned as a theory which has played a useful and honourable part in its day, but has become inadequate to express the developing knowledge of a later time. If so, it ceases to be cited as an accepted theory. Not that Nature has changed, but rather our attitude towards her, and our conceptual model of her phenomena. Thus new theories replace the old ones.

Some years ago the constancy of the chemical elements was, in the then state of knowledge, an accepted theory. Latterly, the phenomena of radio-activity have forced us to believe that radium is passing continuously and spontaneously into other elements—that true transmutations of matter occur. The obvious transmutation of one kind of matter leads to the possibility of the gradual transmutation of all; since as yet no property of matter has been noted which is the exclusive possession of one substance alone. New phenomena, or rather phenomena for the first time appreciated, are continually coming to light, and evidence is accumulating from which the profitable construction of theories—for a time in abeyance—may again be pursued. Nothing must be ruled out of court because contrary to received views; when a *prima facie* case has been made out, everything must be examined by experiment, induction, deduction, and again experiment. This

is the only sure road to the understanding of Nature; and, in times to come, it may lead us into regions now unknown, or considered to be closed to the investigations of science. The evolution and disintegration of matter, the problems of hypnotism and of direct thought transference, are questions which seem to be coming rapidly within the range of scientific inquiry. It is possible that an advance has already been made towards clearing away part of the mystery, so attractive to some, so repellent to others, that surrounds these phenomena. At any rate, in several of the great schools of psycho-medicine, notably in France and America, materials are being accumulated, their trustworthiness examined, and the results systematically collated. It may be that these investigations, so beset with evident difficulties, are indeed indefinitely complicated in their issues by questions of racial predisposition, of individual temperament and mental condition, both of observed and observers. Whether any or all of these problems will prove amenable to the methods of dispassionate observation and experiment is a matter which the years to come alone can show.

We must thus look on natural laws merely as convenient shorthand statements of the organised information that at present is at our disposal. But when Physical Law, as understood in the eighteenth century, has been dethroned from a place that was never rightly its own, let us not think that its usefulness has been diminished or its dignity unduly lowered. Without the possibility of discovering such laws, and framing theories of

their meaning, mankind would be lost hopelessly in a wilderness of phenomena; no continuous progress could be made; no consistent idea of the world around could ever be attained. Each individual phenomenon, as it appeared time after time, might still be investigated; but, with his limited mind and short life, no one man could ever secure a basis for adequate knowledge. Without some general way of stating his experiences, he could hand on neither his guesses after truth nor his hard-won information: mankind would never have emerged from barbarism.

The relations between an observer and his surroundings may for convenience be analysed into the conceptions of length, time, and mass. From these, as we have seen, the other mechanical units can be derived, and a mechanical model of Nature be constructed. It is incomplete; for even the simplest mechanical fact, such as the fall of a body to the ground, inevitably has other aspects. Heat may be developed, electrical manifestations appear, and, if the body be a living one, physiological and psychological changes take place. Neglecting these aspects, however, a complete mechanical account of the phenomenon can be given in terms of the three fundamental conceptions. As we have seen, new ideas, which may be derived from the primary ones, become necessary in the course of the investigation. The body falls with a certain *acceleration*, and, at any instant, is moving with a definite *velocity*. As it falls, it acquires *energy of motion* and loses *energy of position*.

During the fall we find that we can success-

fully describe what happens by assuming that the quantity which we call the mass of the body keeps constant, and that the sum of the two kinds of energy keeps constant also. If we include in our view the complete physical and chemical aspects of the phenomena, we may greatly extend these results. When the body reaches the earth, it is possible that processes of decay set in, which eventually result in most of its substance disappearing in gases or other products. The energy of motion acquired by the body during its fall also seems to disappear, with no corresponding gain of energy of position. Chemistry, however, generalising from many experimental results, tells us that, if we could trace all the forms of matter into which the body is resolved, we should find that there was no loss. Every particle of the original body still exists in one of its products. Physics, on the other hand, teaches us in the same way that the sum of all the forms of energy, heat, sound, etc., which appear as a consequence of the impact on the ground, could they all be taken into account, would be exactly equivalent to the energy of motion possessed by the body at the instant before contact. These great principles of the conservation of mass and the conservation of energy are two of the most important practical generalisations ever reached by Physical Science.

While fully recognising the importance of these generalisations from the physical point of view, we must be careful how we give them any metaphysical significance even under the pre-relativity theory of science. Under certain limiting conditions, other physical quantities besides mass and energy may be conserved. Thus in pure mechanics

we recognise the conservation of momentum—a name for the mathematical quantity obtained by multiplying together the measures of mass and velocity. Again, in reversible systems, where physical or chemical changes may occur in either direction with equal freedom, thermodynamics indicates the conservation of another quantity, named by Clausius, entropy. Momentum and entropy are only conserved under restricted conditions; in physical systems the momentum of visible masses is often destroyed, while in irreversible processes entropy always tends to increase.

Mass and energy may seem to be conserved in the conditions known to us, and we are justified in extending the principle of their conservation to all cases where those conditions apply. It does not follow, however, that conditions unfamiliar to us do not exist, in which mass and energy disappear or come into existence. The persistence of matter, for instance, might conceivably be an apparent persistence. A wave, travelling over the surface of the sea, seems to persist. It keeps its form unchanged, and the quantity of water in it remains unaltered. We might talk about the conservation of waves, and, perhaps, in so doing, be as near the truth as when we talk of the persistence of the ultimate particles of matter. But the persistence of the wave is an apparent phenomenon. The form of the wave indeed truly persists, but the matter in it is always changing—changing in such a way that successive portions of matter take, one after the other, an identical form. Indications are not wanting that only in some such sense as this is mass persistent. In a later chapter we shall see that there is definite

experimental evidence to show that the mass of a moving particle increases as its velocity approaches that of light. Moreover, the principle of relativity has changed profoundly our outlook on such results as the conservation of matter and energy. The concepts in which they are expressed are relative to an observer and not absolute. We may have unconsciously arranged the cards, and then rediscovered with enthusiasm fours and sequences put in by ourselves.

Even if we assume that some reality underlies phenomena, it is clear that the reality must be very different from the mental picture which common sense frames, when unaided by the inductions of science. Our first conception of a wooden stick involves the ideas of a certain long-shaped form, of hardness, of weight, of a colour more or less brown, perhaps of some amount of elasticity. Examination with a microscope reveals many appearances invisible with the unaided eye, and we find that the stick has a structure much more detailed than we imagined. From the results of observation and experiment, physics teaches us that the properties of the stick can only satisfactorily be represented by the hypothesis that the substance of it is divisible, but not infinitely divisible; that it consists of discontinuous particles or molecules. Again, chemistry assures us that the molecules of the stick are made up of still smaller parts or atoms, which separate from each other when chemical action occurs, when, for instance, the stick is burnt, and can afterwards rearrange themselves into new molecules.

When we pursue our inquiries into the nature

of these chemical atoms, we find that recent research has shown that they contain very much smaller particles or corpuscles, and we are asked to imagine that these are in constant motion within the atom, somewhat as the planets move within the solar system. Intimate relations exist between the properties of these corpuscles and the phenomena of electricity, and a corpuscle may be regarded as an isolated electric charge, or electron, as it is called, the mass of the corpuscle being an apparent effect due to electricity in motion.

Thus we have "explained" electricity in terms of corpuscles, and mass perhaps in terms of electricity. Adventurous pioneers may strive to reach more ultimate conceptions by resolving the electron into a centre of intrinsic strain in an æther or a kink in a four dimensional continuum of space and time. Whatever fate may await their efforts, we have already travelled far in attempting to construct a complete mental image of the wooden stick and all its known properties. We have reached ideas very different from those of the hard, continuous substance from which we started.

The other properties of the stick can be analysed into physical conceptions in much the same way. Thus the colour is found to be due to a sorting action which the particles of the wood exert on the complex system of æthereal waves, making up white light. Some of these waves have their energy more freely absorbed by the molecules of the wood than have others; the balance of light is upset, and the reflected beam produces the sensation of colour. Here, again, the most fundamental conceptions into which modern science enables us to resolve our primitive

ideas are very different from those in which they took their origin.

While Natural Science is not committed to any particular philosophical system, while in its essence it is independent of all such systems, the language it uses habitually is based on the common-sense realism, which is the philosophic creed of most men of science—indeed, of the great bulk of mankind, or at all events, of that part of mankind belonging to the races of Western Europe. The mass and energy with which we deal in physical experiments, and in the mathematical reasoning based on inductions from the experiments, are purely conceptual quantities, introduced to bring order and simplicity into our perceptions of phenomena. Perhaps they are not absolute quantities at all, but merely relations between ourselves and the systems we describe in terms of them. They may be replaced by other concepts as our changing knowledge requires.

Possibly the quantum, or unit of "action," which we are forced to accept though it accords ill with previous ideas, may be nearer reality. But science still talks of matter and energy as though it knew of the existence of realities corresponding with the mental images to which alone these names strictly apply. In the laboratory, as in practical life, there is neither room nor time for philosophic doubt. In periods of reflection, however, when considering the theoretical bearing of the results of our experiments, it is sometimes well to remember the limitation of our present certain knowledge, and the purely conceptual nature of our scheme of Natural Science when based merely on its own inductions.



CHAPTER III

THE LIQUEFACTION OF GASES AND THE ABSOLUTE ZERO OF TEMPERATURE

“Scientia et potentia humana in idem coincidunt, quia ignoratio causæ destituit effectum.”—BACON, *Novum Organum*.

MATTER is known to us in three states—as solid, as liquid, and as gas. The relations between these three states have been the subject of investigation throughout the history of Physical Science, and, indeed, almost throughout the history of the human race. The solidification of water in a frost, and its evaporation by the sun or a fire, have been familiar to mankind from the earliest times. But water shows these changes of state under too favourable an aspect to be taken as a general example. It has by no means always been clear that such transformations were possible to all kinds of matter, and it has been necessary to exhaust the resources of modern civilisation to liquefy the more permanent gases.

Ice, when heat is supplied, begins to melt at a definite temperature, which is called 0° on the Centigrade scale, and 32° on the scale devised by Fahrenheit. While any ice remains, no change of temperature occurs in the mixture of ice and water. Heat is still absorbed, but its energy is used to effect a change of state, not to raise the

temperature. The pure substance ice has a constant melting-point. Similarly, if water be cooled at constant pressure, it begins and finishes to freeze at the same temperature. It has a constant freezing-point, identical with the melting-point.

When water boils, a still larger quantity of heat is absorbed, but the temperature again remains unaltered during the whole process. When the barometer stands at 760 millimetres, or just under 30 inches of mercury, the temperature of the boiling-point is taken as the second fixed point on our thermometers, and called 100° or 212° according as we use the Centigrade or the Fahrenheit scale. If the barometer stands higher or lower than the standard height, the boiling-point of water is found to be above or below 100° C., rising or falling through 1° C. for a change of 27 millimetres in the barometer. The freezing-point also depends on the pressure; but the change is much smaller than in the case of the boiling-point, and delicate experiments are necessary to determine it.

The variation with pressure of the points of transition from one state of matter to another are connected with the changes of volume which simultaneously occur. Water expands on freezing, for ice floats on the surface of a lake, and pipes burst in a frost. If this increase in volume be resisted by an external pressure, as by putting the water into a strong closed vessel, the act of freezing involves the performance of external work in forcing outwards the walls of the vessel to give room for the ice to form. It is therefore more difficult to produce ice under pressure, and a greater lowering of temperature is necessary.

Thus an increase of pressure must lower the melting or freezing-point. On evaporation, the increase in volume occurs with the change from liquid to vapour ; an increase of external pressure therefore makes evaporation more difficult, and consequently produces a rise in the boiling-point. If the change in volume and the amount of heat required to produce the change in state are known, the principles of thermodynamics enable us to calculate the exact amount of alteration in the freezing or boiling-points.

There is reason to suppose that the three states of solid, liquid, and gas, assumed within a moderate range of temperature and pressure by the familiar substance water, might be obtained with all bodies if we could command temperatures and pressures high enough and low enough. Metals melt and volatilise at high temperatures, while even gases such as air and hydrogen have now been liquefied.

Several gases, previously unknown in any other form, were liquefied by Faraday. His method consisted in evolving the gas by heating chemical reagents in one limb of a bent glass tube, and cooling the other limb in cold water or a freezing mixture. As the gas is evolved, the pressure rises, and either the gas is liquefied in the cold limb, or the tube bursts. By this simple means chlorine, sulphur dioxide, ammonia, and a few other gases may be liquefied.

The conditions necessary for liquefaction were not fully understood till Andrews, in 1863, showed that carbonic acid gas could not be liquefied unless its temperature was reduced below a

definite fixed point, which he called the critical point. The critical point of carbonic acid is fairly high, about 30° on the Centigrade scale; but for other gases, such as air or hydrogen, it is much lower, many degrees below the freezing-point of water. However low it be, unless a gas is cooled to its critical point, no pressure, whatever be its intensity, can produce liquefaction. Below their critical points, gases may be considered as vapours, and will liquefy if the pressure applied is high enough. The problem of the liquefaction of a refractory gas is thus solved if we can produce cold sufficiently intense to reduce it below its critical point.

Three methods have been used, either singly or in conjunction, to cool gases below their critical points. The first method depends on the heat which it is necessary to supply in order to evaporate a liquid. A liquid boils when the pressure of its vapour is equal to the pressure of the atmosphere acting upon its surface, and, if we reduce this external pressure, the boiling-point is lowered. Thus, by pumping away the vapour as fast as it is formed, and so keeping the pressure low, a liquid can be boiled at a temperature much below its normal boiling-point. By this method, for example, it is possible to make water boil with no outside supply of heat. The heat necessary for evaporation is then taken from the water itself, which in this way is gradually cooled. If the air-pump is efficient, and if very little heat is allowed to leak in, the cooling may go so far that the remaining water is frozen. Beginning at the normal boiling-point of water, we should then have cooled the system by means of evaporation

through 100° . If, instead of water, we had taken some liquid of low boiling-point, such as liquefied sulphur dioxide, or, better still, liquefied carbonic acid, the same process of cooling under exhaustion would have taken place; but the final temperature reached would have been much lower.

Starting then with some substance like sulphur dioxide, which is easily liquefied by pressure alone at ordinary temperatures, we can boil it away under exhaustion, and so produce a low temperature. By making a more refractory gas, such as carbonic acid, circulate through a tube surrounded with the cold sulphur dioxide, this new agent is cooled below its critical point, and liquefied. In its turn the liquid carbonic acid is boiled away under low pressure, and used as a refrigerating agent to cool the gas—oxygen, let us say—which we are attempting to conquer. This, sometimes called the cascade method of cooling, was the plan adopted by the Swiss physicist, Pictet of Geneva, in the experiments which, simultaneously with those of his French contemporary Cailletet, first liquefied oxygen. With one of those curious coincidences which the broad wave of advancing knowledge sometimes produces, both these results were announced at a memorable meeting of the French Academy, held on the 24th of December 1877.

Even when the gas was thus cooled, however, Pictet's process was not entirely effective. In order to pass the last few degrees and reach the critical point, a second method of cooling had to be brought into play. To explain this second method other principles must be taken into account. When a certain mass of gas, forced into

a closed vessel till the pressure rises to several atmospheres, is let out suddenly, its volume is, of course, greatly increased by the sudden expansion. Room has to be made for the increase of volume, and this process requires the expenditure of work, for the atmosphere is pressing on the gas on all sides, and has to be forced back when the expansion occurs. Moreover, if the particles of the gas attract each other, work must be done in the separation necessary for the increase of volume. Thus internal as well as external work may be performed during the expansion. Unless heat is supplied from without, the energy needed to perform all this work must come from the heat supply of the gas itself, which becomes cooled in the process. If the expansion is sudden and therefore rapid, there is no time for heat to enter the gas, and the cooling represents the full effect of the work done. By this means, Pictet finally liquefied his oxygen. The highly compressed gas, which had been cooled in liquid carbonic acid boiling under low pressure, was allowed suddenly to escape into the atmosphere. A large amount of external work was thus done, intense cooling resulted, and liquid oxygen was seen as spray in the issuing jet of gas. It was by a still more sudden expansion that Cailletet liquefied oxygen, using preliminary cooling only to 30° below the Centigrade zero.

In modern forms of apparatus for the liquefaction of gases it is found advisable to sacrifice the cooling gained by the performance of external work, and to rely on that due to the internal work alone. By this means it is possible to construct much more powerful and efficient refrigerating

machines. The essential feature in the process of cooling by the performance of external work is the expansion of the gas by its own elastic force. If the work necessary for the increase of volume under the external pressure be supplied by an engine, or if all such work be prevented by making the gas expand into a vacuum, there is no external work to absorb the heat energy of the gas itself, and no cooling from this cause is produced. The gas, however, still has to supply any work needed to separate its own particles against any mutual attractive forces, and, if such forces exist, cooling can still be obtained at the expense of the heat-energy of the gas. On the other hand, if the inter-molecular forces are forces of repulsion, expansion will be aided by their action, and will, in the absence of external work, be accompanied by an increase of temperature. Thus, by arranging for free expansion, as it is called, we can examine the nature of the inter-molecular forces by observing whether a gas is cooled or heated.

In such experiments, it is necessary to prevent the performance of external work by the gas itself, and this can be done in either of the two ways indicated above. Gay Lussac, and afterwards Joule, filled one vessel with gas under high pressure, and then allowed the gas to expand into another vessel previously exhausted. Here, in expanding into a vacuum, no external pressure has to be overcome, and no external work is done. Any thermal change will be the equivalent of the internal work. The vessels were placed side by side in water, which was stirred after the experiment, and tested with a sensitive thermometer. At ordinary temperatures no heating or cool-

ing could be observed with any of the gases examined.

The apparatus just described is clearly not adapted to detect small thermal changes, and it was not till about the year 1850, when Thomson and Joule devised a continuous method, that satisfactory results were obtained. Instead of preventing external work by allowing the gas to expand into a vacuum, these physicists performed the external work needed to expand the gas against the pressure of the atmosphere by means of an air-pump driven by an engine. By this method a continuous current of gas was forced through a porous plug of compressed wool or silk, fixed in a wooden tube. Here the engine does the external work, and consequently none of that work draws on the heat energy of the gas itself.

All the external work is done by the engine, but, as we have seen, another source of energy-change exists. When a gas expands, whether or not it performs external work, the various parts of it become separated further from each other, since, on the whole, the gas occupies after expansion a larger volume than before. If, then, there is any attraction between the parts of the gas, work must be done in separating them; in terms of the molecular theory, work is done against the inter-molecular forces. For the performance of this internal work, energy must be drawn from the heat-supply of the gas, which will therefore cool, and the amount of cooling, if access of heat from outside be prevented, measures the intensity of the inter-molecular forces. On the other hand, if the inter-molecular forces be

repulsive ones, they help on the expansion, and the energy so liberated appears as sensible heat, the resultant rise of temperature depending on the strength of the repulsion between the molecules.

The porous plug experiment, to which we have referred on the last page, was devised by Professor William Thomson, afterwards Lord Kelvin, and the late Dr Joule, for the purpose of examining the amount and nature of these inter-molecular forces, and of determining the amount of deviation of various gases from the ideal state, in which no such forces exist. If a thermometer were filled with such a hypothetical ideal gas, its indications would coincide exactly with the absolute temperature scale, deduced by Thomson from the principles of thermodynamics. The knowledge of the deviation of any real gas from the ideal state thus enables us to compare the absolute scale with the scale of an actual thermometer, using the expansion of the gas in question as the thermometric property. The great theoretical importance of the porous plug experiment will now be manifest.

Thomson and Joule found that air, and all other gases except hydrogen, were cooled slightly on passing the plug; with hydrogen, on the other hand, they obtained a still smaller heating effect. Thus in hydrogen the molecules must on the whole repel each other, while in air and similar gases, the intermolecular forces must be attractive ones. The amount of the effect was found to increase in proportion to the difference of pressure on the opposite sides of the plug.

With air the cooling effect decreases as the temperature is raised, and increases if the air

be cooled. The change of temperature produced, which was only one-fifth of a degree per atmosphere difference of pressure in the original experiments, can thus be increased to any extent by a preliminary cooling of the air.

This cooling by the performance of internal work underlies the third method adopted in the liquefaction of gases. It must be distinguished clearly from the second method, in which most of the cooling is effected by making the gas do external work.

Let us imagine that a stream of air, previously cooled by liquid carbonic acid, is forced through a spiral tube by aid of an air-pump and engine, and that finally it merges through a fine nozzle at the end of the tube. The nozzle acts as a porous plug, and the air, cooled by free expansion, is lowered in temperature by doing internal work. Let us further suppose that the issuing air, so cooled, is made to flow back over the tube through which the stream of air passes. The advancing current of air is still further cooled, the effect of the expansion at the nozzle is increased, and a temperature yet lower than before attained. This cycle of operations—the continual passage of the air just cooled by free expansion over the current of air before it issues from the nozzle—results in a constantly decreasing temperature, and eventually cools the air below its critical point, finally causing liquefaction. This self-intensifying action is sometimes referred to as the regenerative principle. It was applied to the liquefaction of air by Linde in Germany, by Hampson and Dewar in England, and by Tripler in America, and is now used on large scale machines.

Liquid air can be obtained in any quantity by the expenditure of power, and the necessary apparatus has become part of the usual equipment of physical and chemical laboratories. By this means regions of temperature before quite inaccessible have been opened up to investigation, and the use of liquid air promises to be of increasing advantage in many departments of research. It would, of course, be possible to drive an engine by means of liquid air, but such a process would be very uneconomical. The statements, which have sometimes appeared in the daily papers, announcing impending revolutions in methods of obtaining cheap power by the application of liquid air, have originated from an imperfect comprehension of the problems involved.

When air had been successfully liquefied, hydrogen was obviously the next gas to be attacked. Thomson and Joule's porous plug experiments had shown that, at ordinary temperatures, hydrogen suffers a heating effect on free expansion. It was therefore useless to attempt to liquefy it by regenerative cooling alone. But, just as the cooling effect in the case of air increases as the air is subjected to a preliminary cooling, so in hydrogen, if it be first cooled, the Thomson-Joule heating effect first diminishes and then is reversed, becoming a cooling effect. This reversal was shown by Olszewski to take place about 80° below the Centigrade zero. Dewar then subjected hydrogen to a preliminary cooling in liquid air boiling in a vacuum at a temperature of -205° , and afterwards forced the hydrogen through a regenerative coil under a pressure of 180 atmospheres.

By this means liquid hydrogen was first collected in an open vessel on 10th May 1898, though two years before it had been seen as spray in the jet of gas issuing from a simpler apparatus of the same essential form. When about 20 cubic centimetres of liquid had been collected, the later experiment failed, owing to the stoppage of the exit by frozen air—a very common accident in dealing with liquid hydrogen.

By working with carefully purified gas, much larger volumes were soon obtained, and the writer has a vivid memory of an afternoon in June 1901, when Professor Dewar had transported some five litres of liquid hydrogen from the Royal Institution to the rooms of the Royal Society, and gave his first public demonstration of its extraordinary properties. On that occasion liquid hydrogen flowed like water for the first time. Its production in any quantity is now simply a matter of expense.

By carefully isolating a portion of liquid hydrogen and preserving it, in a manner shortly to be described, from the access of heat from without, it is, when suddenly exhausted under an air-pump, transformed into a mass of solid frozen foam. By immersing a tube containing the liquid in this frozen foam, a quantity of the clear transparent ice of solid hydrogen can be obtained.

Kept in an open vessel, liquid air and liquid hydrogen are analogous to the water in a saucepan boiling over a fire. At the normal atmospheric pressure, water boils at 100°C. , and the rate at which it evaporates depends simply on the rate at which heat enters it—depends, that

is to say, on the fire below. In a similar way, liquid air has a definite boiling-point, which, under the normal pressure of the atmosphere, rises from -192° to -182° C. as evaporation proceeds. This rise is due to the fact that nitrogen is more volatile than oxygen; and thus the liquid, as it boils away, gradually becomes richer in oxygen. Liquefied air cannot be kept in closed vessels. Its vapour pressure, equal to the pressure of the atmosphere at -190° , becomes enormously great as heat enters from surrounding objects and the temperature rises. In an open vessel, as heat enters evaporation proceeds, and the heat is used to effect the change of state. Thus, owing to this latent heat of evaporation which is absorbed, no rise of temperature (except the very small change already noted) occurs. But, in a closed vessel, as heat enters the pressure will rise, and the boiling-point will rise with it. The initial temperature being so low, a large rise of temperature is possible, and a consequent very great increase in pressure. As ordinary temperatures are approached no vessel would withstand the internal pressure of the evaporating air.

In order to preserve liquid air for any time in an open vessel, it is clearly necessary to prevent as far as possible the access of heat. Evaporation must be proceeding continuously, but, by diminishing the rate at which it goes on, the rate of loss of liquid can be retarded.

Heat passes from one place to another in three ways: by conduction, when heat flows from one part of a body to another, or between two bodies in contact; by convection, when air or water, heated by contact with a hot body, rises

through the colder surrounding fluid, carrying heat with it; by radiation, when heat passes directly from one body to another, as from the sun to the earth, without warming the intervening medium. Bearing in mind these three modes of transference, Professor Dewar invented a

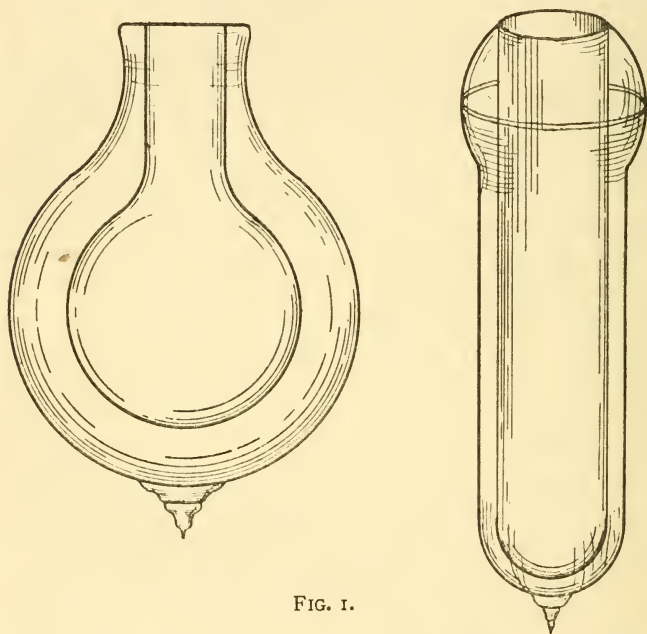


FIG. 1.

vessel in which a liquid gas can be kept, and the effects of all three of these methods of heat-transfer be reduced to a minimum—the now well-known thermos flask.

A double-walled glass bulb was taken, of one of the forms shown in Fig. 1, and the space between the walls exhausted of air to the completest degree possible. This arrangement diminished

the effects of conduction and convection to such an extent that liquid air, placed within, evaporated at only one-fifth of the normal rate. An additional device enabled the effects of radiation to be diminished also. A polished metallic surface is the worst radiator and the worst absorber of radiation known, and, by coating the opposite walls of the vacuum space with a film of bright silver or mercury, the rate of evaporation of liquid air was again reduced to the sixth part. By the combined results of the vacuum and the silvering, the rate of loss of liquid was thus reduced to the thirtieth part of its value in an ordinary open vessel. Without the use of these vessels, liquid air could not be kept for any length of time, and liquid hydrogen, at any rate, could never have been collected at all.

With the liquefaction of hydrogen the old class of so-called permanent gases disappeared. In place of them, however, a number of gases, previously unknown to science, have been discovered. Argon, shown by the late Lord Rayleigh and Sir William Ramsay to exist in the atmosphere, was the first of these gases to be detected. Its name attempts to describe its general chemical inertness; and since this discovery several other new gases of somewhat similar chemical properties have been detected.

The story of the discovery and isolation of argon is an excellent example of the importance in science of the infinitely little, and shows how striking discoveries may be made as a consequence of experiments which seem at first sight simply adapted to investigate, with the greatest

attainable accuracy, phenomena already known to science. Since the days of Cavendish, the composition of the air had been looked upon as an ascertained fact; a certain proportion had been shown to be oxygen, varying amounts of carbonic acid and aqueous vapour were known to be present, while the remainder, as the result of careful investigation, was supposed to be nitrogen. Cavendish himself knew, so accurate was his work, that any undetected residue could not exceed the $\frac{1}{120}$ th part. But in the course of a long series of experiments, undertaken to determine afresh the densities of the principal gases, Lord Rayleigh detected a slight difference in the density of nitrogen as prepared from ammonia and as extracted from the air. This difference, amounting at first to about 0.1 per cent., was increased on subsequent more careful examination to nearly a half per cent. It was clear that the gases prepared by these two methods were not identical, and that some hitherto unknown body was responsible for the complication. The existence of this new body, the inert gas now known as argon, was announced by Rayleigh and Ramsay in 1894, and shortly afterwards it was isolated from its companions.

Argon is slightly more soluble in water than nitrogen, hence a rather larger proportion of it than might be expected is found in rain water. It is also contained to a small extent in the gases liberated from certain thermal springs. Traces of three other gases, neon, krypton, and xenon, which much resemble argon in chemical properties, have been detected in the atmosphere. The total amount of these three substances is almost im-

measurably small, and does not altogether exceed the four-hundredth part of the argon present.

The spectrum of the sun shows some lines which do not coincide with those of any chemical element in conditions usually known on the earth. Among these lines many are due to terrestrial elements in solar circumstances, but a bright line in the yellow part was detected in the spectrum of a solar prominence, and was examined carefully by Frankland and Lockyer during the eclipse of August 1868. To explain its presence they called into existence a hypothetical element, placed it in the sun, and gave to it the name helium. For many years the line in the sun's spectrum was the only evidence for the existence of helium; but in 1895 its presence on the earth was announced by Ramsay, who had detected it in the spectroscopic analysis of the gases dissolved in the mineral cleveite, together with the other new gases krypton and neon. Since this discovery, helium has been isolated and collected in appreciable quantities, and its physical and chemical properties are now well known. Of all substances investigated, helium has proved the most difficult to liquefy. But in July 1908, Professor Kamerlingh Onnes, of Leyden, obtained liquid helium for the first time by the use of a regenerative apparatus and a plentiful supply of liquid hydrogen.

It will be seen from the foregoing account that the difficulty of obtaining these low temperatures is very great. While a temperature of many hundred degrees above the freezing-point of water is easily reached in a common fire or gas flame, to cool hydrogen to 250° below that point

needs the use of powerful engines, of elaborate and costly apparatus. The difference is very marked. Moreover, it becomes more and more difficult to cool a substance through one degree as we pass down the scale. This fact suggests that there is some lower limit of temperature towards which we may strive, but with the prospect of encountering increasing difficulty as we approach; it suggests, that is to say, the existence of an absolute zero of temperature.

Our knowledge of an absolute scale of temperature is due to the genius of Lord Kelvin, who, with Clausius, Rankine, and Helmholtz, may be said to have founded the modern science of thermodynamics about the year 1850. It can be shown that Lord Kelvin's absolute scale of temperature coincides with the scale of an ideal gas—a gas, that is, such as air would be if its molecules exerted no forces on each other, and, consequently, its porous-plug-effect were nil. As a matter of fact, at ordinary temperatures and pressures, such gases as air or hydrogen conform very nearly to these conditions—so nearly that, for all ordinary purposes, their deviations may be neglected. Now, if we keep a gas at constant pressure, its volume changes from 1 to 1.366 as it is heated from the freezing to the boiling-point of water. Similarly, if it be kept at constant volume, its pressure increases in the same ratio. If we use either of these changes as our thermometric property, and divide the interval between the freezing and boiling-points into 100° in the Centigrade manner, there will be a change in pressure, for example, of 0.00366 or $\frac{1}{273}$ of the



Helvin
Feb 11, 1904

Photo by Window & Grove.]

pressure at 0° , for each degree through which the gas is heated. If we call the pressure at 0° unity, then at 1° the pressure will be $1 + \frac{1}{273}$, at 2° it will

be $1 + \frac{2}{273}$, and so on. Similarly, if we cool the gas below the freezing-point, at -1° the pressure becomes $1 - \frac{1}{273}$, at -2° the pressure is $1 - \frac{2}{273}$.

If, while we carry on this process, the properties of the gas remain unchanged, as they would were it the ideal gas we have supposed, at a temperature of -273° the pressure will fall to $1 - \frac{273}{273}$, that is,

$1 - 1$, or zero. At -273° C., therefore, the pressure of an ideal gas would vanish absolutely, and no further cooling could make it smaller. On the temperature scale which uses the pressure of an ideal gas as the thermometric property, -273° C. represents an absolute zero, the lowest conceivable degree of cold. But, as we said, such a scale coincides exactly with the true absolute or thermodynamic scale, which, as can be shown, unlike all other temperature scales, is independent of the properties of any particular substance, whether real or imaginary. On the thermodynamic scale also, then, -273° C. represents the absolute zero.

We thus see that the idea of an absolute zero, at which all bodies would be deprived entirely of heat energy, is not a mere figment of the mathematical imagination, derived from the study of a hypothetical air thermometer. It has a real physical meaning, and the attainment of the absolute zero is, at all events, theoretically possible.

From the practical side, however, difficulties accumulate and increase as the absolute zero is approached. As Sir James Dewar remarked, "the step between the liquefaction of air and that of hydrogen is, thermodynamically and practically, greater than that between the liquefaction of chlorine and that of air." The boiling-points of chlorine, air, and hydrogen under the atmospheric pressure are -33° , -193° , and -253° C. respectively. If we express these temperatures on the absolute scale, they become 240° , 80° , and 20° . The interval between the boiling-points of chlorine and air is 160° , but the ratio of the absolute temperatures is $240:80$, or $3:1$. On the other hand, while the interval between air and hydrogen is only 60° , the ratio of the absolute temperatures is $80:20$, or $4:1$. The difficulty of the transition from one to the other temperature is much more nearly proportional to the ratio than to the difference between them.

The absolute boiling-point of hydrogen is, as we have said, about 20° , and at present this temperature is the lowest which we can conveniently maintain in an ordinary laboratory. Any further advance towards the absolute zero must be made by the help of helium. By the sudden expansion of gaseous helium at a pressure of 100 atmospheres and at the temperature of solid hydrogen, it was estimated that a transient temperature of 9° or 10° absolute was reached. When that gas was liquefied, Professor Onnes found that its boiling-point under the normal atmospheric pressure was about 4.5° on the absolute scale. This temperature is about one-

fourth the boiling-point of hydrogen, and it has proved at least as hard to pass the interval between hydrogen and helium as it was to pass from air to hydrogen.

But, as was foreseen, the liquefaction of helium was effected by an extension of methods previously successful with other gases. A preliminary study of its properties showed that, after cooling in liquid hydrogen, it should cool further when subjected to a regenerative process. After attempts by several investigators had failed, Professor Onnes succeeded, and the year 1908 saw the last known refractory gas reduced to the state of liquid.

The liquefaction of helium gives command of a steady temperature of about $4^{\circ}.5$ absolute, its boiling-point in open vessels. That temperature, within 5° of the absolute zero, is thus possible, and Onnes has reached perhaps a degree lower by working under low pressure; but there, with our present methods and materials, seems to come the end of any probable advance.

We may now pass to a brief account of the methods of measuring these very low temperatures.

Mercury freezes at a temperature of -40° C., and, at such temperatures as those now under consideration, a mercury thermometer clearly is useless. The resistance of a metallic wire to the passage of an electric current is a quantity which can be measured easily and accurately. This resistance, diminishing as the wire is cooled, depends on the temperature. With some alloys the diminution of resistance with temperature is very small, but with pure metals it is considerable, and roughly, at any rate, proportional to the

change of temperature. The metal most usually employed is platinum, since it is not attacked by acids, and has a very high melting point. Platinum thermometers are now used extensively for physical research ; they have a very large range, and are probably susceptible of greater sensitiveness than any other form of thermometer. At ordinary temperatures a difference of temperature of one ten-thousandth of a degree can be detected with moderate ease, while, with great precautions, the hundred-thousandth of a degree can be estimated. At high or low temperatures such accuracy is impossible, but measurements, correct to the nearest degree, can be made up to about 1100°C . and as low as -200°C . Below the latter temperature the rate of change of the resistance alters in a manner to be described below, and the instrument ceases to be trustworthy.

The standard to which the readings of all other thermometers are referred, as we have indicated when considering the absolute scale of temperature, is the gas thermometer containing hydrogen or helium. Not only is the hydrogen thermometer thus used for purposes of reference, but it can also be employed as a practical instrument at temperatures too low to be measured by the platinum resistance thermometer. It might be thought that, as the point of liquefaction was approached, a gas would cease to be trustworthy as a thermometric substance, but experiment has shown that, as long as the pressure of the gas is kept well below the saturation value at which condensation would occur, the gas still expands or contracts proportionally to the absolute temperature. Dewar has found that thermometers,

filled with oxygen and carbonic acid at low pressures, gave correct temperatures as low as the boiling-points of those gases at the normal atmospheric pressure. He used therefore a constant volume hydrogen thermometer, working at low pressure, to determine the boiling-point of liquid hydrogen itself, and confirmed the result obtained, -252°C. , by experiments with a similar thermometer filled with helium.

Some very remarkable effects are obtained with liquid hydrogen. A vessel containing it is so cold that the air in contact with it immediately freezes. A snow-shower of solid air is thus produced. This process may be applied to the production of very high vacua. If the vessel to be exhausted be sealed to a long tube, one end of which is plunged into liquid hydrogen, the air in the vessel is frozen out almost completely. The air in the cooled end of the tube first condenses, but, as it is removed, the residual air in the vessel expands, again fills the whole tube, and again that portion of it in contact with the cold part of the tube is frozen. This process continues till the pressure within the tube falls to the millionth of an atmosphere or less, a pressure so low that an electric discharge will only pass through the vessel with extreme difficulty. A vacuum nearly complete may also be obtained by using charcoal cooled by liquid air in place of the hydrogen.

The liquefaction of air and hydrogen has led to the making of many experiments on the influence of low temperature on chemical action, and it is found that the rate of change is very

greatly affected at these temperatures. In many cases, where the reaction proceeds rapidly at ordinary temperatures, the rate is reduced to such an extent that in liquid air it becomes too small to be observed. In other cases action may cease altogether, and reagents which would otherwise undergo chemical change are maintained in false equilibrium by chemical forces analogous to those of friction. Fluorine, for instance, which attacks glass violently at ordinary temperatures, has no effect on it when cooled to -180°C .

It is found that the elasticity of materials is greatly affected by these low temperatures. On the one hand, iron, lead, and tin, as well as ivory, showed a considerable increase in this property, balls of these substances rebounding to a much greater height than usual. On the other hand, a ball of india-rubber became brittle, and was broken by the fall. Connected with the increase in the elasticity of metals is their increased strength; wires, for example, will stand a much greater load without pulling out or breaking.

Low temperatures also affect the magnetic properties of iron, cobalt, and other metals, which are usually magnetic at ordinary temperatures, generally increasing the magnetic moment. Oxygen, slightly magnetic as a gas, as a liquid becomes strongly magnetic. The alteration of magnetic properties with temperature has been studied in detail for many years where high temperatures are concerned, and this extension of the research has been of great interest.

Of even more theoretical importance are the experiments of Onnes on the electrical conductivities of metals at the very low temperatures

obtained with liquid helium. As explained above, the electrical resistance of a pure metal increases generally nearly in proportion to the absolute temperature, and diminishes equally as the temperature falls. Nevertheless, most metals seem to reach a constant small resistance as they approach the absolute zero, and this residual resistance is increased by traces of impurities.

But Onnes discovered that with pure mercury he got a sudden and almost complete destruction of resistance at $4^{\circ}.2$ absolute, a sudden drop in resistance to about the millionth part. He got similar effects with tin at $3^{\circ}.8$ and with lead at 6° absolute, but other metals which he examined gave no such results. The conductivity is so high that an electric current once started in a coil of wire continues to flow almost indefinitely, falling in strength by less than 1 per cent. per hour.

Applying a magnetic field of slowly increasing strength, Onnes found that, at a certain critical magnetic force, tin and lead when cooled to these temperatures gave a sudden increase in resistance, an observation which shows that this state of super-conductivity is connected with magnetic phenomena. Its real meaning is not yet clear, though tentative theories of the state have been offered by Onnes, Lindemann, and Thomson.

From the point of view of the popular lecture-room, some of the prettiest effects given by liquid air depend on its power of imparting phosphorescence to many substances which do not usually possess this property. Ivory, egg-shells, paper, cotton-wool, and many other things glow brightly in liquid air after they have been exposed to light. On the other hand, certain sulphides of calcium,

phosphorescent at ordinary temperatures, cease to be so when cooled. Some crystals, such as those of uranium nitrate, become self-luminous in liquid hydrogen, apparently owing to intense electric forces set up by the cooling. These forces may become so intense that discharges take place which are powerful enough to be visible in the dark.

It will be seen from this account that the changes in physical properties are more striking and complete in the range of temperature below the freezing-point of water than in the corresponding range of temperature above that point. On the other hand, it is very striking that in biological problems, more especially in those connected with the lowliest forms of animal and vegetable life, a hundred degrees above the freezing-point is productive of a more complete and destructive change than a hundred degrees below. While exposure to the boiling-point of water, or to a temperature a few degrees higher, suffices to kill all known forms of living organisms, many forms of bacteria merely have their vitality temporarily suspended in liquid air. Even seeds of barley, peas, etc., were not permanently affected; in fact, they have been placed for six hours in liquid hydrogen with no effect on their subsequent power of germination.

In closing this account of low temperature research it may be of interest to tabulate some of the more important temperature-constants now known to mankind. In doing so, we cannot fail again to be struck by the high temperatures easily obtainable. On the other hand, to cool an

object through 250° of the 273° which separates the freezing-point of water from the absolute zero has taxed the skill of experimenters for several generations. Temperatures, as already pointed out, are more justly compared by considering their ratio on the absolute scale than by considering the number of degrees Centigrade or Fahrenheit which separate them.

	Temperature.	
	On Absolute Scale.	On Centigrade Scale.
Zero of the absolute scale	0°	-273°
Boiling-point of liquid helium	$4^{\circ}\cdot5$	$-268^{\circ}\cdot5$
Boiling-point of liquid hydrogen	20°	-253°
Critical-point of hydrogen	30°	-243°
Boiling-point of liquid air	81° to 91°	-192° to -182°
Boiling-point of liquid carbonic acid	195°	-78°
Freezing-point of water	273°	0°
Boiling-point of water	373°	100°
Melting-point of tin	505°	$231^{\circ}\cdot7$
Melting-point of lead	601°	$327^{\circ}\cdot7$
Boiling-point of sulphur	718°	$444^{\circ}\cdot5$
Melting-point of silver	1234°	$960^{\circ}\cdot7$
Melting-point of gold	1335°	$1061^{\circ}\cdot7$
Melting-point of copper	1354°	$1080^{\circ}\cdot5$
Melting-point of platinum	2073°	1800°

Approximate Temperature
on Centigrade Scale.

Low red heat	500° to 600°
White heat	1500° „ 1800°
Temperature of furnace	1500° „ 1600°
Temperature of electric arc	3000° „ 4000°
Estimated temperature of the radiating layer of the sun	5700° „ 7000°
and of the hottest stars	$23,000^{\circ}$

CHAPTER IV

FUSION AND SOLIDIFICATION

For more is not reserved
To man, with soul just nerved
To act to-morrow what he learns to-day :
Here work enough to watch
The Master work and catch
Hints of the proper craft, tricks of the tool's true play.
—BROWNING, *Rabbi Ben Ezra*.

IN the previous chapter we have discussed chiefly the methods employed to bring about a change of state, especially that change of state which consists in passing from the gaseous to the liquid or solid condition in the case of those substances which at ordinary temperatures and pressures exist as gases. The methods employed and the principles underlying them were the points of interest, and the whole subject belonged to that branch of physical science which consists in recognising and overcoming difficulties of manipulation, and, as it were, of asserting by force the superiority of mind over matter.

But, throughout the investigations to be pursued in the present chapter, our attitude is altered. There is no need for such attempted assertion of supremacy. The changes of state to be examined are already under our control, and we are able to investigate further details, and probe more deeply into the intimate nature of the processes involved. We patiently seek to

trace connections between, for example, the mechanical properties of metals and their microscopic structure when solidified; and, from the complicated relations which declare themselves, we may hope to throw light on the processes of fusion and solidification, and construct a theory that will hereafter prove of some use to the engineer and the metal-worker.

In the first place it is well to remark that we are seldom dealing with pure materials. Nearly the whole of the phenomena we shall consider depend on the admixture of two or more substances, one for the most part predominating. It follows that the result of the inquiry is specially applicable in all cases where traces of some impurity are the determining factor; that is, to the majority of cases, since the attainment of chemical purity is more often a pious hope than an accomplished fact.

Our investigations will lead us far afield, and we shall pass in review combinations of many of the principal metals. It is well, however, that the starting-point should be on familiar ground; if, indeed, by such a term it is permissible to indicate the ice that occasionally covers our ponds and perpetually caps our globe.

It is well known that sea-water remains liquid at temperatures low enough to freeze ponds and lakes, and, long ago, it must have been recognised that this behaviour was due to the dissolved salt, though it was not till the year 1788 that Blagden, the first worker in the field, published a systematic series of observations on the freezing-points of salt solutions.

If we cool the solution of some substance such as sodium chloride, that is, common salt, the ice which freezes out is the solid form of pure water. The process can be illustrated in a very striking manner by using the solution of a coloured salt. If, for example, a dilute solution of the purple-coloured potassium permanganate be placed in a glass bottle and be surrounded for some hours by a freezing mixture, most of the water solidifies to form a hollow cylinder of perfectly colourless ice, while the permanganate is concentrated in an intensely coloured liquid core along the axis of the cylinder.

Similar phenomena occur in other cases where the separation is not so clearly visible.

If the ice be frozen rapidly, some trace of salt may be deposited also ; but experiment has shown that it does not enter into the composition of the crystals, and is entangled merely mechanically in their interstices. Essentially, then, the salt remains in the liquid solution, and, as the solvent is gradually frozen out, the concentration of that solution must increase. The stronger the solution becomes, the lower is its freezing-point ; but, if the temperature at our disposal be low enough, we can go on freezing out water till the residual solution is saturated with salt at the temperature of its freezing-point. Any further abstraction of heat, by removing some of the necessary solvent, must then be accompanied by the simultaneous deposition of salt ; ice and salt will be precipitated together, and the residual solution will retain the constant composition of saturation.

Since, as the process of freezing goes on in these conditions, there is no change in the

composition of the residual liquid, there can be no change in the freezing-point. The mixture of salt and water of this particular concentration will solidify completely at a constant temperature into a mixture of salt and ice of the same composition. But pure chemical elements like lead, or pure compounds like water, also fuse and solidify at constant temperatures without change of composition. In these respects, then, the particular mixture of salt and water which we are considering behaves like a pure element or compound. For this reason Guthrie, who first systematically examined such mixtures, classed them as compounds, and named them cryohydrates. It is, however, now evident that their properties are explicable in other ways.

The phenomena we have traced, and the existence of a cryohydric point must be borne in mind if we wish to understand the structure of natural ice, the properties of metallic alloys, or the processes which occur when, in the cold of an Arctic winter, sea-water becomes coated with a solid covering.

Natural waters, even when known as fresh, contain some amount of solids in solution. When such waters are cooled to the freezing-point, however, the crystals which appear form the ice of pure water. As the crystals grow, the dissolved salts become concentrated into the liquid which remains; and the freezing-point of this liquid falls as its concentration rises. Unless the temperature of the cryohydric point is reached, some liquid must always remain, though, with fairly pure water, it may exist only as a thin film between the solid crystals. If the temperature

sink below the cryohydric point, these liquid films themselves solidify ; but, even then, the mass is not a homogeneous solid, for the cryohydric conglomerate forms a cement-like connection between the primary crystals of pure ice. We see now the explanation of the fact that a block of natural ice, taken from a glacier or lake, has a definite structure, and may be resolved into a heap of separate crystals by exposure to the sun. The cryohydric cement dissolves first at the lower temperature, and thus the primary crystals of pure ice fall away from each other before the temperature rises to their melting-point.

Phenomena precisely similar to those we have described appear when a fused metal is allowed to solidify. Crystalline structures of pure metal form in the liquid, and grow till the whole mass becomes solid. These primary crystals usually start as fernlike forms, of which a beautiful example is shown in Fig. 2. This represents the microscopic structure of a bronze ingot, suddenly chilled from a temperature of 644°C . If the crystals be allowed to grow by very slow cooling, they may come to fill nearly the whole mass, as in the case of the section of iron shown in Fig. 3. Even in this case, with a substance nearly as pure as can be obtained, the lines of separation between the primary crystals are clearly visible ; the primary crystals are differently orientated, and their faces reflect the incident light at different angles. The crystals of zinc are often remarkably large and well defined, and fine specimens can be seen on surfaces of so-called galvanised iron, such as is used for water-cisterns,



FIG. 2.
Magnification 45.



FIG. 3.
Magnification 200.

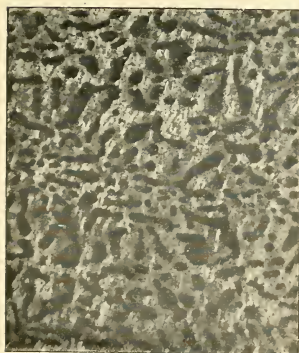


FIG. 4.
Magnification 50.

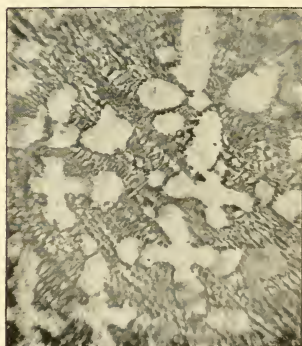


FIG. 5.
Magnification 120.

etc. When, instead of a single metal, traces of others are present, the lines of separation between the primary crystals are much emphasised, and, when the quantity of other substances is considerable, there arise the complicated structures, which we shall presently study under the head of alloys.

The process of the freezing of sea-water under the influence of the intense cold of an Arctic climate is an interesting example of the application of the same principles. The phenomena have been described by the explorer, Weyprecht, whose account is quoted by Mr J. Y. Buchanan in his "Chemical and Physical Notes." When a new surface of sea-water is exposed to the cold air, in a short time the surface of the water begins to get thick, threads like a spider's web running out from the old ice. Brine is entangled in this structure, and its concentration constantly becomes greater as the quantity of ice increases. At this stage the ice is a pasty mass, and follows every motion of the water on which it floats. With a temperature of -40°C . the new ice, even after twelve hours, is still so soft that, in spite of its thickness, a stick can easily be thrust through it.

As soon as a layer of ice is formed over the surface, the cooling of the underlying water proceeds much more slowly, and less salt is entangled in the crystals. The lower layers of sea-water ice give therefore, when melted, a much fresher water than can be obtained from the upper layers. Even when strong enough to walk on, the surface of new sea-ice, frozen by air at -40° , is still moist and soft, the residual liquid consisting of a concentrated solution of various salts, chiefly

calcium chloride. The cryohydric point of calcium chloride, an extremely soluble substance, is very low, and that of a mixture of salts will be lower than that of either component. This lowering of the cryohydric temperature, which corresponds with the lowering of the freezing-point of water by the addition of salt, was observed by Buchanan in experiments conducted in the Engadine.

So far the components of the system we have been considering are not miscible with each other in all proportions; only a limited amount of salt can be dissolved in a given quantity of water. A system not subject to any such restriction, in which the phenomena are as simple as possible, is found in mixtures of the metals silver and copper. The equilibrium of these substances was studied by Mr C. T. Heycock and the late Mr F. H. Neville, who determined the melting-points, or rather the points of solidification, of mixtures of various proportions of the two metals. At the high temperatures involved, it would, of course, be impossible to use a mercury thermometer, and the measurements were consequently made by means of a platinum resistance thermometer, with which the temperature is determined by observing the electrical resistance of a coil of platinum wire. The metals in the required proportion are fused in a crucible and allowed to cool. As soon as solidification sets in, the rate at which the temperature falls always becomes less; and, in the case of pure metals and other systems where the solid has the same composition as the liquid, the temperature remains constant till solidification is complete, just as the tempera-

ture of a mass of ice and water remains constant till the whole is frozen. Thus, by watching the thermometer, the temperature at which solid begins to form can be estimated.

The melting-point of silver is 960°C . and the addition of copper lowers it just as the addition of salt lowers the freezing-point of water. This is best shown by plotting the observations on a diagram, as in Fig. 6, in which the horizontal axis

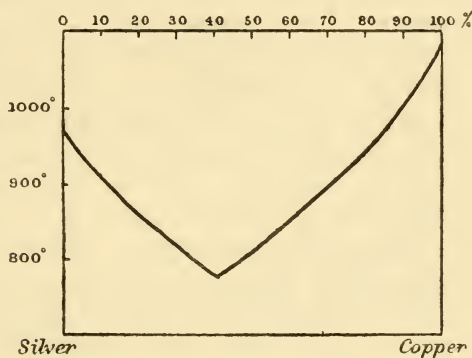


FIG. 6.

denotes the composition of the mixture expressed in percentage numbers of atomic equivalents of silver and copper, and the vertical axis the temperatures. On the other hand, pure copper melts at 1081° , and the admixture of silver lowers its freezing-point. The two curves in the diagram cut each other at a point which corresponds with a temperature of 777° , and a composition of 40 atomic percentages of silver and 60 of copper. At other points on the curves, the process of freezing consists in the separation of primary crystals of one or other of the pure metals in the

manner we have traced for solutions in water.¹ The point of intersection of the curves corresponds with the point of saturation both of silver with copper and of copper with silver. When the fused alloy has this proportion, crystals of silver and copper freeze out together, just as crystals of salt and water freeze out together when the composition of the solution is that of the cryohydrate. The point we are considering, then, corresponds with the cryohydric point for salt and water. The composition of the solid is here the same as that of the liquid, and therefore, as the process of solidification goes on, the residual liquid always has a constant concentration. Thus the freezing-point remains constant throughout the operation, and is identical with the melting-point at which liquid first appears when the solid alloy is heated. Similar phenomena constantly appear in the study of other metals; and if an alloy of this composition is polished, etched with acid, and examined under a microscope, it will be seen to consist of a uniform conglomerate of the two kinds of crystals. An alloy of any other proportion exhibits larger primary crystals of that metal which is present in excess, and was frozen out first, connected by regions filled with the conglomerate referred to above. On account of its more uniform texture, this conglomerate, which, as we have seen, corresponds with a so-called cryohydrate, is named the eutectic alloy. Fig. 4, on the plate facing

¹ Osmond thinks that, in this particular case, the primary crystals are not perfectly pure. He adduces evidence to show that a slight trace of copper is dissolved in the solid crystals of silver. Any such effect, however, is hardly appreciable.

page 72, represents a microscopic photograph of the eutectic of gold and aluminium; while in Fig. 5 is shown the structure of an alloy with a composition not quite that of the eutectic. Here large primary crystals have appeared, the intervals being filled with the same eutectic which is seen in Fig. 4. The metal of Fig. 4 has been cooled more slowly than that of Fig. 5, and therefore the eutectic in Fig. 4 has larger crystals and a coarser structure.

The eutectic alloy has a constant melting or freezing-point; but, during the process of fusion or solidification of other alloys, the temperature will generally change. As the primary crystals of one or other pure metal form, they leave the residual liquid richer in the other constituent, and thus with a lower freezing-point. This process continues till the liquid has the composition of the eutectic alloy, when any further loss of heat will precipitate crystals of both metals side by side. A thermometer immersed in the mixture will show the temperature at which primary crystals begin to form, and the temperature at which the composition of the residual liquid reaches that of the eutectic, for the rate at which it falls becomes suddenly much slower when solid first appears, and the fall stops altogether while the eutectic is freezing out. Thus, in such a simple case as that of silver and copper, useful information can be obtained by merely drawing the curve giving the observed relation between the time and the temperature for the heated alloy. Such curves have forms more or less resembling that shown in Fig. 7.

With silver and copper no chemical compounds

are formed ; with many pairs of metals combination occurs, and the phenomena are more complicated. A definite chemical compound plays a part similar to that of a pure element. Addition of either component lowers the freezing-point of the compound. Thus the point of solidification of the pure compound must correspond with a maximum point on the equilibrium curve. If a single compound is formed by the two components, the curve must consist of three branches ;

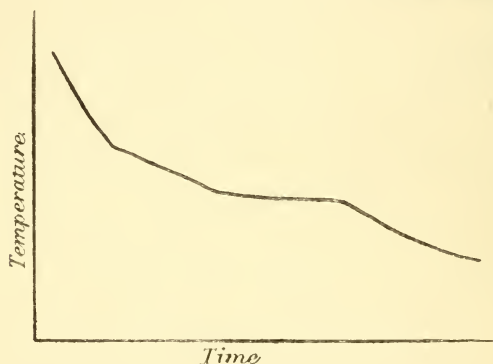


FIG. 7.

a branch due to the effect of the compound being interposed between two branches similar to those in the silver-copper curve just considered. Copper and antimony form a single compound SbCu_2 , in which two atoms of copper are united with one of antimony. The equilibrium of the solid and liquid phases has been studied by M. Le Chatelier, whose results are illustrated in Fig. 8. In this case two eutectic alloys are formed ; one being a conglomerate of crystals of the compound with those of copper, and the other containing crystals

of the compound and crystals of antimony. These eutectics are represented by the points *a* and *c* in the figure, and between them rises the curve showing the effect of the compound, which exists in the pure state at *b*, the maximum of the curve.

In all the cases yet considered, the crystals deposited consist either of a pure metal or else of a pure chemical compound. Whichever it be,

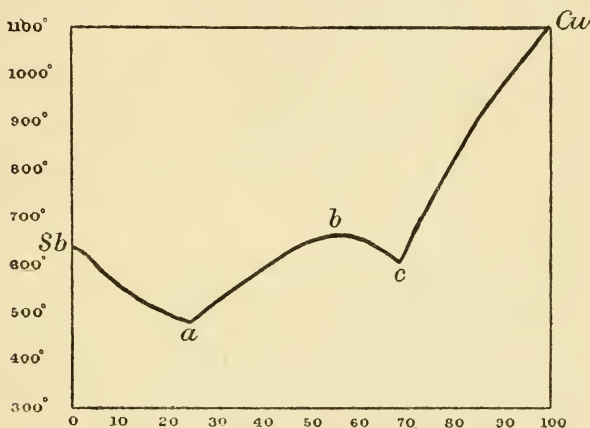
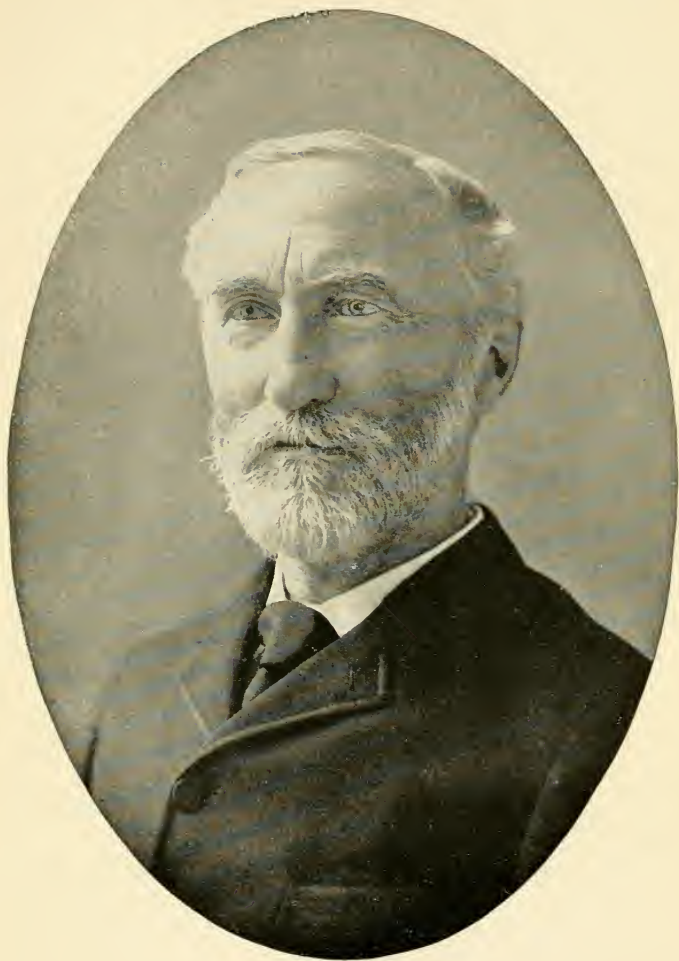


FIG. 8.

the composition of any one crystalline species is fixed and definite; it does not vary continuously when the composition of the mass of alloy is altered, as does, for example, the composition of the fused liquid. In Fig. 6, p. 75, the left-hand branch of the curve gives the composition of the liquid alloy which, at different temperatures, is in equilibrium with crystals of pure silver, while the right-hand branch represents the liquid in equilibrium with pure copper. One phase only,

the liquid, can vary continuously in composition ; the other, or solid, phase is fixed and invariable. Similarly in the case illustrated in Fig. 8, the crystals of the compound SbCu_2 have a fixed and constant composition. Cases are known, however, in which the solid phase also varies continuously. Many salts, such as the different alums, are of the same crystalline form, and can replace each other gradually in a crystal, which may have any composition between that of the two pure salts. Such structures are called mixed crystals or solid solutions. When they can exist, the phenomena of equilibrium become much more complicated, for the composition of the solid will vary as well as that of the liquid, and will introduce a second curve into the freezing-point diagram.

It is only of recent years that it has been possible to interpret the complicated phenomena of solid solutions. Now, however, we possess a consistent theory of the subject, founded by Professor Roozeboom of Amsterdam, on the work of the late Professor Willard Gibbs of Yale University. Long ago, in the years 1875 to 1878, Gibbs published a series of mathematical papers in the *Transactions* of the Connecticut Academy. For some time they remained practically unknown to European physicists ; then they were discovered by Clerk Maxwell, who used a few of the results in his book on the "Theory of Heat." But even then the time was not ripe, and it is only of recent years that we have realised that the whole theory of chemical and physical equilibrium is contained in Gibbs' work. Buried for so long, the seed has germinated in the minds



J. WILLARD GIBBS.

of many investigators. It has already borne good fruit, and is probably destined to bear still more in time to come. Happily, Willard Gibbs lived to see a general recognition of his genius, and the reputations made of younger men who knew how to extract and apply even single results taken from the rich store hidden in his somewhat abstruse pages.

By the use of Gibbs' thermodynamic principles, Roozeboom was able to trace the various possible

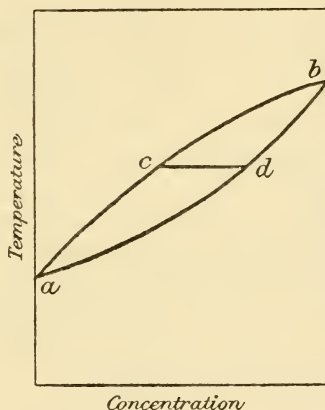


FIG. 9.

forms which can be assumed by the two curves, representing the compositions of the liquid and solid phases in equilibrium with each other. The simplest case indicated by the theory is shown in Fig. 9. In regions above the higher curve, *acb*, which is called the "liquidus," all points represent states completely liquid, while below the curve *adb*, or "solidus," the alloy is entirely solid. Between these curves exist both liquid and solid in various proportions. At a definite temperature,

a liquid of one composition, say c , is in equilibrium with a solid of another composition, such as d . As the process of solidification proceeds, the composition of both liquid and solid changes continuously. In the light of these theoretical curves, the complicated experimental curves, found by observing the freezing-points of mixtures of metals and of other substances, are now being interpreted in a manner which otherwise would have been quite impossible.

One of the most successful examples of such an interpretation is given by the very thorough study which was made by Heycock and Neville of the bronzes, that is, of alloys consisting of copper and tin. The curves in Fig. 10 show the results of their own experiments and of previous work by Roberts-Austen. Heycock and Neville examined microscopically the structure of various alloys of the two metals in conjunction with the equilibrium curves, and gave us a knowledge of the bronzes more complete than that which we then possessed for any other series of alloys showing phenomena of an equal degree of complexity.

Fig. 10 shows the equilibrium curves, from pure copper on the left to an alloy containing 80 atomic percentages of tin on the right. Above the "liquidus" ABCDEFGH the alloys consist of a homogeneous liquid, in which solid first begins to form when the temperature falls to points represented on the curve. The "solidus" curve, below which the whole mass is solid, is the complicated curve $Ab_lcmef_{E_2}E_4H''M$.

It has long been known that the physical properties of metals, especially of alloys, depend on the way in which they are cooled from a state

of fusion. The whole process of the annealing or tempering of steel depends on a perception of this fact. Many observers had studied the changes of physical properties thus produced by examining microscopically the solid alloys obtained by different treatments, and relations between the properties of the alloy and its microscopic structure

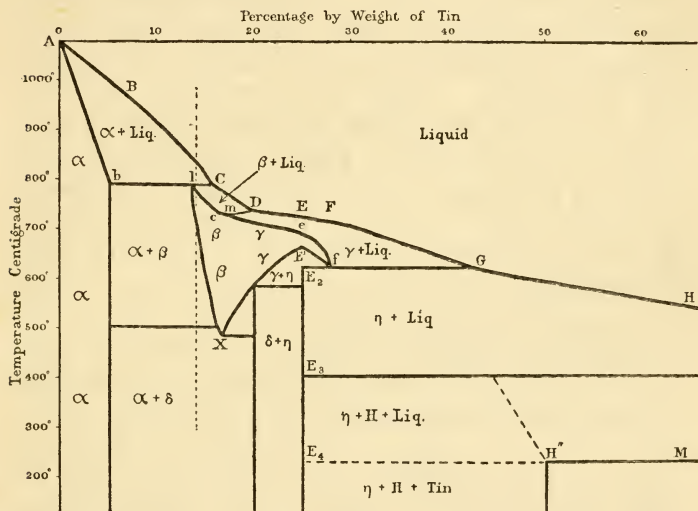


FIG. 10.

had been traced. But for the first time a complete investigation was made by Heycock and Neville of the changes in microscopic structure produced by different methods of cooling, and studied in conjunction with the equilibrium curves by the light of the theory of solid solutions. The work was rendered possible by the fact that, if a hot metal be cooled suddenly from any temperature by chilling it in cold water, the microscopic

structure it possessed at that temperature is stereotyped almost perfectly by the process of sudden chilling, and can be examined at leisure in the cold metal by polishing and etching it with acid in the usual manner.

In this way equilibrium curves lying below the solidus were detected and traced. Such curves represent changes of structure which occur in a mass completely solid, and quite explain the changes in physical properties caused by annealing or chilling. Take as an example the two curves $\angle x$ and $E'x$, which cut each other in the point x , and recall in their general form and relations the simple curves of equilibrium between liquid and solid for alloys of silver and copper already described and illustrated in Fig. 6 (p. 75). The analogy is more than one of mere form. Just as crystals of silver or copper separate out of the homogeneous liquid of Fig. 6, so crystals of new substances separate out of the homogeneous solid solution which exists within the triangular space $\angle xfl$ in Fig. 10; and, as the crystals of silver or copper are in equilibrium with the liquid alloy in states represented by points on the freezing-point curves of Fig. 6, so the new crystalline structures are in equilibrium with the homogeneous mother substance lying within our present triangle.

The positions of these curves of equilibrium between solid phases are investigated chiefly by the microscopic examination of ingots of metal, which are fused, allowed to cool very slowly to the temperature to be investigated, in order that, as far as possible, equilibrium may be reached, and then suddenly chilled by immersion in cold water. A section of the ingot is polished, and

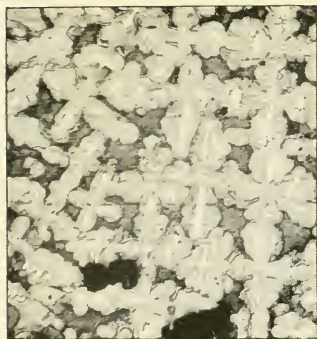


FIG. 11.—Magnification 18.



FIG. 12.—Magnification 45.

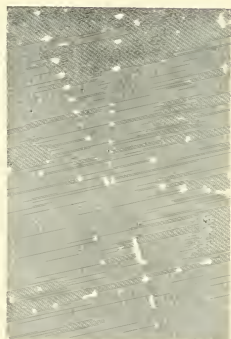
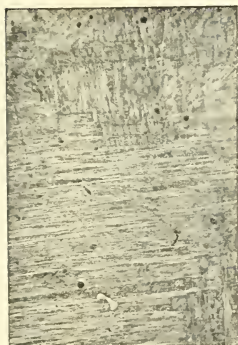


FIG. 13.—Magnification 18.

FIG. 14.—Magnification 18.

FIG. 15.—Magnification 18.



FIG. 16.—Magnification 18.

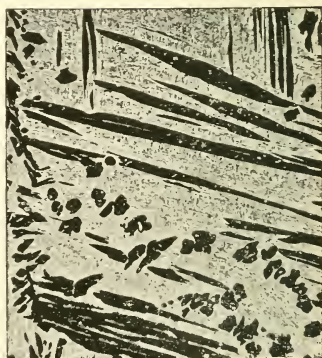


FIG. 17.—Magnification 18.

etched with acid or other suitable liquid, in order to bring out the structure-pattern. Each pure metal, compound, or solid solution, crystallising from the mother liquid, possesses a characteristic appearance, which can readily be recognised after some practice in interpretation of the micro-photographs. Such photographs enable us to trace the formation, development, and decay of new crystal-species in a liquid or in a solid matrix.

The effect on the microscopic structure of differences in the rate of cooling is well shown in Figs. 11, 12, and 13. The same alloy is represented in all these photographs, and was, in each case, chilled from about the same temperature. The differences in structure depend solely on the differences in the rate of cooling from a liquid condition to the temperature at which the ingot was chilled in cold water.

The alloy contained 13.5 atomic percentages of tin, and is represented by the vertical dotted line in Fig. 10. When this alloy in cooling passes the liquidus ABC, crystal skeletons of a solid solution called α appear mixed with the mother liquid. These skeletons somewhat resemble the larger fern-like structures of Fig. 2 on p. 72, which, however, chosen chiefly for its beauty, was taken from a bronze of another composition.

When the alloy we are now considering passes the line lc (Fig. 10), a new kind of crystalline solid solution, called β , begins to form; and, if time is given it by keeping the ingot hot, the β substance gradually eats up the existing crystals of α . This process is

illustrated in Figs. 11, 12, and 13. In Fig. 11 the residual α is seen as white cores within the grey β , which follows the arrangement of the original α structures, while, in the particular illumination employed, the part that was liquid at the instant of chilling shows as a dark background. In Fig. 12, where the ingot was cooled more slowly, the change has gone farther; the β substance ceases to follow the original skeletons of α , a higher magnification brings out the characteristic striated appearance of the β , while, owing to a different illumination, the mother liquid shows as a light background. Fig. 13 is taken from an ingot which had been cooled to the same chill point exceedingly slowly, and kept many hours just above that temperature. The whole ingot is now filled with uniform striated β , a tiny speck of α , seen towards the lower side of the photograph, alone remaining. In the light of these three photographs it is not surprising that the physical and mechanical properties of metals are modified profoundly by differences in the rates at which they have been cooled from a fused condition.

Following the dotted line in Fig. 10 still further, we see that, in ingots chilled from temperatures about 750° , β alone should exist. Fig. 14 shows a chill from 740° , which was cooled to that temperature almost slowly enough to destroy all the primary crystals of α , which now only show as scattered specks of white.

Again following the dotted line in the equilibrium curve of Fig. 10, we pass the boundary λx , and again enter a region where α and β exist together. The facts on which this curve is

based are illustrated in Fig. 15. Here a new or secondary crop of α crystals has begun to grow. This ingot was chilled at 558° , and there is no doubt that the new growth of α took place in a mass which had solidified completely long before.

The further growth of the new α is seen in Fig. 16, which represents an alloy of slightly higher content of tin (14 atomic per cents.) chilled from a temperature of 530° . As the alloy in cooling passes the temperature of 500° , the whole of the β substance is transformed into a complex consisting of α crystals intimately mixed with a new solid solution called δ . This complex is shown in Fig. 17 as a light background; while, in contrast with it, the α crystals come out dark after the treatment adopted.

These changes again occur in a mass thoroughly solid throughout, and explain in a most striking manner the effect of such processes as annealing and tempering, in which the properties of a metal are altered by heating it to a temperature well below its fusion-point and then cooling it either slowly or rapidly.

Heycock and Neville's investigation of the bronzes was a very laborious undertaking. One hundred micro-photographs were published, and these represent only a selection of those taken; many observations of freezing-points were also made. But the labour of the work is well repaid by the magnificent results finally obtained.

Iron and steel, as used in the arts and industries, consist of pure iron alloyed with various substances, chiefly carbon. Solid solutions, similar

to those we have studied in other cases, are formed between iron and carbon, and the phenomena of equilibrium between the liquid and solid phases, even when no other component is present, are very complicated.

Owing to their industrial importance, the alloys of iron have been investigated more extensively than those of any other metal, and the various compounds and solid solutions identified have received definite names, which, in many cases, were given long before the application by Roozeboom of the theory of solid solutions enabled the true phenomena of equilibrium to be understood. Roozeboom's diagram for alloys of iron and carbon, containing less than 7 per cent. of carbon, is reproduced in Fig. 18. Its general meaning will be clear in the light of what has been said in the case of the bronzes. Here again changes occur at definite temperatures, even in alloys which are completely solid. The viscosity of the material makes these changes very slow, and very different proportions of the various possible constituents will be found in alloys that have been cooled quickly and slowly. The effects of tempering steel and iron thus receive a physical explanation.

By heating iron above one of the transformation temperatures indicated in the diagram, and maintaining it at a high temperature for some time, it will obviously be possible to produce extensive changes in the physical nature of the metal. Experiment by Mr J. E. Stead has shown, that when steel rails have become dangerously brittle and crystalline by long use, they can be reconverted into a tough, elastic, and therefore

safe condition by prolonged heating at temperatures from 850° to 900° C. This improvement in properties has been traced to the development of a constituent of the alloy known as sorbite. It is this constituent which gives the peculiar

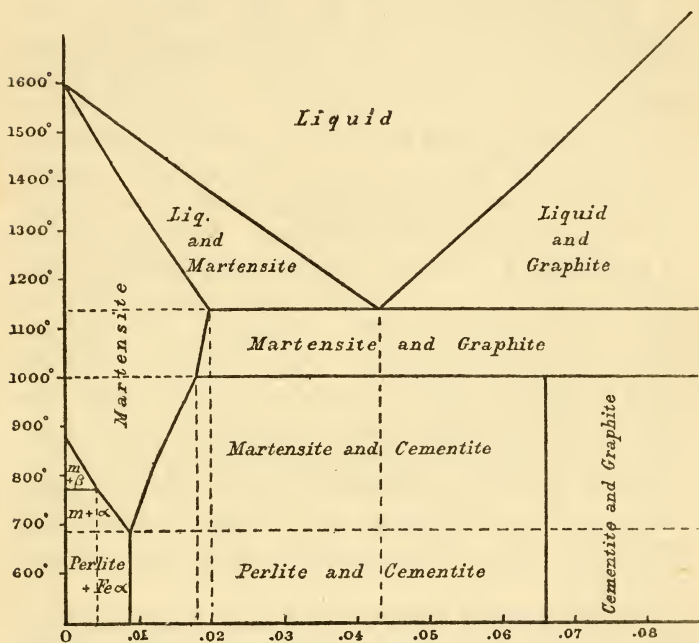


FIG. 18.

tenacious properties to iron which has been specially prepared for drawing into wire.

Microscopic studies of the alloys composing iron and steel have been very numerous. The work of Sorby, Andrews, Osmond, Le Chatelier, and Stead should particularly be mentioned. It is by such microscopic investigations that the different constituents of the alloys have been for

the most part distinguished, the crystals of each constituent having a characteristic appearance, which usually persists throughout a series of changes.

The investigations we have described all emphasise one point—the fact that metals possess a structure essentially crystalline. In some cases, such as that of the surfaces of zinc deposited on so-called galvanised iron, this crystalline structure is readily visible, but most of the metallic objects in common use possess polished surfaces on which no trace of crystals can be seen. The possibility of polishing a surface to such a state of perfection that it will act as a mirror and reflect a ray of light without appreciable scattering, is a matter of considerable interest. Any irregularities on such a surface must be small compared with the wave-length of light, and it is difficult to see how any such surface could be obtained by the use of ordinary polishing materials, if the action of these materials be regarded as a mere mechanical grinding away of projections after the manner of a file.

Many careful observations have been made on the process of polishing. Among them should be noted those published in August 1903 in the *Proceedings of the Royal Society*, by Sir George Beilby. He investigated the subject microscopically, and found reason to believe that the passage over the surface of a scratched metal of a polishing substance like wash leather covered with rouge produces a kind of surface flow, the outer layers of the metal flowing like a viscous liquid under the action of the pressure on the polishing tool,



FIG. 19.—Magnification 775.

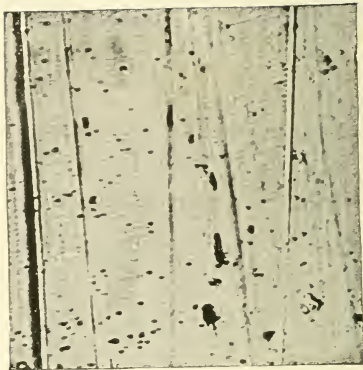


FIG. 20.—Magnification 775.

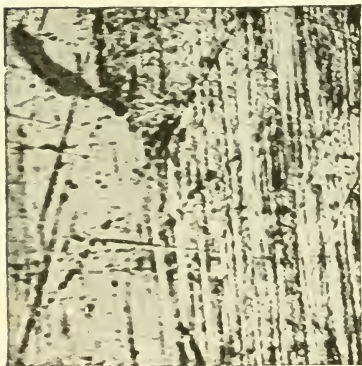


FIG. 21.—Magnification 775.



FIG. 22.—Magnification 775.

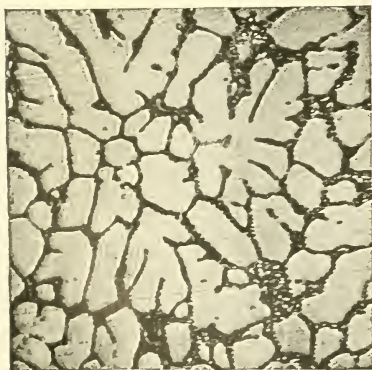


FIG. 23.—Magnification 775.

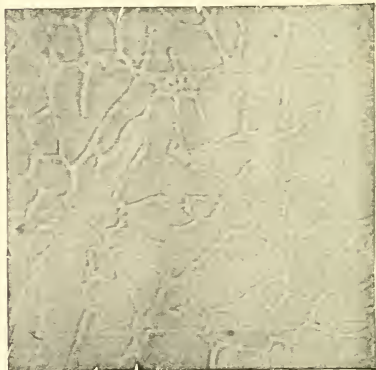


FIG. 24.—Magnification 775.

and assuming an optically perfect surface under the influence of surface tension. In this way a film is formed over the surface of a metal, which film is in a state essentially different from that of the bulk of the substance below. Inside the metal the crystalline forces have full play; at its surface, the controlling influences consist in part of surface tension, which, under the pressure of a polishing tool, is able to overcome the tendency to assume a crystalline structure. In Figs. 19 to 24 are shown six of Sir George Beilby's photographs. Fig. 19 shows the surface of crystalline antimony after rubbing with fine emery paper. The magnification is such that the photograph is 775 times life-size. Fig. 20, which represents the same surface after polishing with rouged leather, shows the gradual dragging of a film of metal over the pits and furrows of the first surface. The larger pits get filled with filings of metal, and the film seems to bridge them over, forming a continuous sheet over the loosely-packed fragments below. When an acid or other liquid capable of dissolving the metal is placed on the surface, the film is dissolved, and the pits and furrows reappear. This comes out in Fig. 21, in which the antimony previously polished has been etched with a solution of potassium cyanide. Fig. 22 shows a polished surface of speculum metal, an alloy used for the reflectors of telescopes. Here the underlying crystalline structure is faintly visible. The surface film has, in Fig. 23, been removed with potassium cyanide, and the structure is now plain, the primary crystals, separated by channels of eutectic alloy, being clearly brought out. Finally, in Fig. 24, the same surface has been repolished,

and the channels bridged over with the flowing film of viscous metal.

These experiments have an interest which extends further than the immediate subject to elucidate which they were undertaken—an experience not uncommon in physical research. The existence of this viscous metallic film under certain conditions suggests that, when minute quantities of a solid alone exist—when there is in effect inside the surface film no substance beyond the range of molecular action—all crystalline structure must disappear. The initial formation of solid in the body of a saturated solution or of a fused material will, on this view, be co-ordinated exactly with the deposition of drops of water from a mass of air saturated with aqueous vapour, and the possibility of super-saturation will, in each case, depend on the work required to form a new surface of separation under the influence of surface tension alone. It is only when the individual solid structures attain a considerable size that crystalline forms begin to appear.

CHAPTER V

THE PROBLEMS OF SOLUTION

"If we accept the hypothesis that the elementary substances are composed of atoms, we cannot avoid concluding that electricity also . . . is divided into definite elementary portions, which behave like atoms of electricity." — H. VON HELMHOLTZ, "Faraday Lecture," 1881.

To one inexperienced in the problems which confront the workers in the world of natural science, the whole question of solution and its attendant phenomena may appear, at first sight, of small account. Yet the study of these same phenomena, and the unravelling of their intricate connections, are of fundamental importance. Furthermore, as the work of the last twenty years has shown, the problems involved are of increasing interest, not only from the point of view of physics and chemistry, but also, and perhaps especially, from the physiological standpoint. More and more the reactions of inorganic substances, whether liquid or solid, are referred to their properties in a state of solution, while every process of life to be investigated by the biologist seems capable of interpretation only through attention to the conditions thereby involved. Moreover, most chemical actions, especially those examined easily in the laboratory, occur between substances one or more of which are actually in the liquid state; while the application

of physical conceptions to the problems of living matter chiefly depends on the knowledge we possess of the physics and chemistry of ordinary solutions.

The earliest investigations of the subject were of a chemical nature, and, till the passage of electric currents through liquids came to be examined at the beginning of the nineteenth century, little systematic study of the physical properties of solutions was made. But since that period there has been constant progress, and many new fields of research have been opened up.

It happens constantly that light is thrown on the dark places of one science by work undertaken to elucidate those of another; and, in this case, the starting-point for the modern theory of solution is found in some experiments made by Pfeffer in 1877 in a botanical laboratory. Ten years earlier, Traube, in studying the modes of formation of the organic cells of plants and animals, had discovered how to construct artificial membranes permeable to water but not to solutions of certain substances dissolved therein. Pfeffer made a further examination of these semi-permeable membranes, as they have been called, and by their use obtained results of great importance in the study of biology.

A porous pot of unglazed earthenware, 6 to 8 centimetres high and 2 or 3 centimetres in diameter, is sealed by means of sealing-wax to a glass tube, as shown in Fig. 25. Having been thoroughly washed, it is filled with the solution of a salt, such as potassium ferrocyanide, and the outside is then surrounded with the solution

of another salt, such as copper sulphate or ferric chloride, which gives an insoluble precipitate

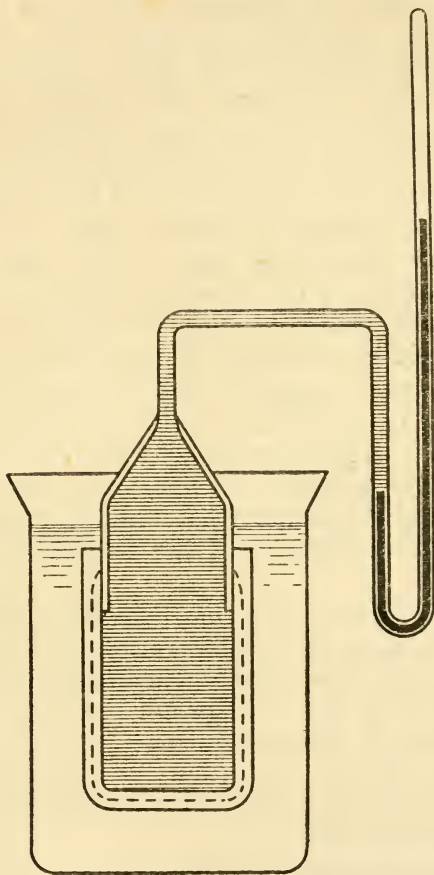


FIG. 25.

when in contact with the first salt. The two solutions gradually diffuse from opposite sides into the walls of the cell, and form an insoluble

membrane, indicated by a dotted line, where they meet inside the thickness of the walls. This process can be hastened, and the resulting membrane improved, by forcing the salts into the porous material by means of an electric current. The solutions are washed away, and the wide glass tube is drawn out and sealed to a smaller tube in the manner shown in the figure.

Inside a cell thus prepared let us place the solution of some substance, such as sugar in water, and surround the outside with a large volume of the pure solvent, in this case, water. Water will gradually force its way into the cell, and, by placing mercury in the glass tube to use as a pressure gauge, it will be found that this influx will continue till a definite internal pressure is reached—a pressure greater than that without. This gives a measure of what is called the osmotic pressure of the solution as it finally exists in the cell after the entrance of the additional quantity of water.

Pfeffer found that this osmotic pressure was proportional to the concentration of the solution, at all events between the concentrations of 1 and 6 per cent. of sugar. For a 1 per cent. solution, the excess of pressure at $6^{\circ}.8$ C. was equal to that of a column of mercury 505 millimetres high, the normal atmospheric pressure being equivalent to 760 millimetres.

Many membranes within animal and vegetable organisms are semi-permeable, or, at all events, are more permeable to solvent than to solution. The permanent or temporary differences of pressure, which are thus set up, are being investigated extensively by physiologists, and



J. H. and P. H.

have already been shown to play important parts in the processes of living structures.

Attention was first called to the interest and importance of osmotic pressure from a physical standpoint by the distinguished Dutch chemist, the late professor Van't Hoff. In 1885 Van't Hoff pointed out that Pfeffer's numbers showed: (1) that the osmotic pressure was inversely proportional to the volume in which a given mass of sugar was confined; and (2) that the absolute value of the pressure in the case of the solution of sugar was the same as that which would be exerted by an equal number of molecules of a gas when placed in a vessel having a volume equal to that of the solution. For instance, a quantity of gas of the same molecular concentration as a 1 per cent. solution of sugar would, at 6°.8 C., exert a pressure equivalent to that of 508 millimetres of mercury, a number identical, within the limits of experimental error, with Pfeffer's observed value for the osmotic pressure quoted above. The first result is equivalent to the extension to dilute solutions of Boyle's law for gases, a law which states the experimental result that the volume of a gas is inversely proportional to its pressure. The second result shows that, in a dilute solution, the pressure depends only on the number of molecules present, and not on their nature—a statement which, applied to gases, is known as Avogadro's law.

But Van't Hoff did not alone call attention to the experimental basis of the new subject. He also placed the theory of it on a sound footing. The amount of a gas which dissolves in a given quantity of water is proportional to the pressure,

and from this experimental result Van't Hoff showed mathematically by the principles of thermodynamics, that, when in solution, this same gas must exert an osmotic pressure of the observed value. The proof involves no assumption as to the physical mechanism by which the osmotic pressure is produced. Whether it be due to the impacts of the dissolved molecules on the semi-permeable walls, in the same way that the molecules of a gas exert pressure on the walls of the containing vessel; whether it be due to chemical affinity between the dissolved substance and the solvent, affinity which causes more solvent to enter the cell; or whether some other hitherto untraced effects come into play, remains an open question. The thermodynamic argument simply shows that, from the experimental solubility relations of gases, the observed osmotic results follow for the gases when dissolved; but the physical *modus operandi* of the pressure remains uncertain.

The extension of the theoretical result to the case of non-gaseous solutes like sugar involves some amount of assumption. However, since substances of all degrees of volatility are known, the extension seems reasonable; and it is abundantly justified by Pfeffer's experimental measurements.

Another method of applying the principles of thermodynamics to this problem has been developed by Willard Gibbs, Von Helmholtz, and Larmor. Whatever view we take of the fundamental nature of a solution, we must imagine the dissolved substance scattered as a number of discrete particles throughout the

volume of the solvent. The nature of the interaction which occurs between the solute and the solvent is unknown, possibly unknowable; but, whatever it may be, each particle of solute will affect only a minute sphere of solvent lying round it. The solution, then, may be regarded as containing a number of little systems, each composed of a solute particle surrounded by an atmosphere of solvent in some way influenced by its nucleus.

While the solution is concentrated, the little spheres will intersect each other, and the addition of further solvent will involve some change in the interaction between solute and solvent. But, in the process of dilution, a time will come when the spheres are beyond each other's reach, and the addition of more solvent merely increases their mutual separation without affecting their internal structure.

Thus, in a dilute solution, the energy-change of further dilution is merely the energy-change involved in separating the particles of the solute; it will not depend on the nature of any possible interaction between the solute and the solvent. The change of energy is thus independent of the nature of the solvent, and will be the same whether that solvent be water, alcohol, or any other liquid. It will even be the same when, in cases where that is possible, the solvent is removed altogether, and the solute is obtained in the gaseous state.

If we imagine that the bottom of a frictionless engine cylinder is made of a semi-permeable membrane, separating a solution within the cylinder from a solvent without, it is easy to see that

osmotic pressure may be made to do work, which will be measured by the pressure multiplied by the change of volume. Thus the osmotic pressure is measured by the change of the available energy per unit increase of volume; that is, by the rate of change in the available energy of dilution.

In this manner we arrive again at the conclusion, that the osmotic pressure must be equal in amount to the gaseous pressure exerted by the same number of molecules when vaporised, and must conform to the laws which describe the temperature, pressure, and volume relations of gaseous matter. The result is seen clearly to be independent of any hypothesis concerning the mechanism of the pressure or the nature of the solution.

In the last chapter we have traced the phenomena of fusion and solidification, and, in the course of our inquiry, studied the equilibrium of liquid solutions with the different solid phases which may exist in contact with the liquids. The fundamental problem of the nature of a solution was untouched; indeed, from the point of view then adopted, such a problem did not arise.

Until the last quarter of the nineteenth century, it was generally assumed that the forces which were brought into play when a solid dissolved in water were of the same nature as those involved in chemical action; and the resulting solution was looked on simply as a chemical compound in which there happened to be no fixed relation between the masses of the components. The study of dilute solutions, and, in particular, the examination of their osmotic pressures, showed that, in many respects, a dilute solution was analogous

to a gas, and conformed to the same laws of pressure, volume, and temperature. Such results emphasised the analogy between the dissolution of a solid and the diffusion of a gas through a space in which it was not originally present, and sometimes led to the idea that the osmotic pressure of a solution, like the pressure of a gas, was due to the impact of its molecules on the containing wall. As an extreme case of this aspect of the phenomena, the view has been expressed that the solvent should simply be regarded as giving room for the diffusion of the molecules of the solid; any possible interaction, of a chemical nature or otherwise, between the solvent and solute being disregarded.

The similarity between the laws of gases and those of dilute solutions, however, does not necessarily connote identity in physical nature; the account of the subject given by thermodynamics shows clearly that the essential feature, common to both cases, on which the similarity depends, is the dilution. In a gas the molecules are, on the average, too far from each other to exert appreciable intermolecular forces, and the change in energy produced by further dilution does not involve such intermolecular forces. In the same way the dissolved molecules in a dilute solution are so far from each other that, whatever be their action on the solvent, they exert none on each other. Here again, the change of energy on further dilution does not involve the forces between those molecules which alone from this point of view are to be considered, that is, the molecules of the dissolved substance. The essential point is the distant separation of the

molecules in each case from each other; any interaction between solvent and solute would not affect the result, and the result therefore cannot be used as evidence for or against such interaction.

The similarity in pressure-volume laws, then, cannot be regarded as determining the question whether solution is, in its essential nature, chemical or physical. To settle such a problem other evidence must be sought. Very little such evidence is yet available; what little there is seems rather to favour the chemical view, which regards a solution, say of salt and water, as in some way a chemical compound of these components; a compound in which the relative proportion between the components can vary continuously between certain wide limits.

The results in this case are characteristic of the methods of thermodynamic theory as applied in physical science. Thermodynamics is not concerned with the physical *modus operandi* of the phenomena. It does not involve molecular hypotheses; it is free from any doubt which accompanies such hypotheses, though it gives less insight into the intimate processes of the phenomena than do successful molecular conceptions.

In the development of several branches of physics and chemistry two stages can be traced. It has sometimes happened that the earliest theoretical account of a subject has been given from the mechanical or molecular standpoint. In this way a definite working hypothesis has arisen, on the lines of which much investigation has been undertaken. Gradually, however, this preliminary scaffolding has been found to be unnecessary, and

a thermodynamic theory has been developed, which connects the phenomena directly, and brings out their relations with similar phenomena in other branches of science.

The two methods may perhaps be illustrated in some such way as the following. In looking at the face of a watch, certain relations are observed between the positions of the two hands at different times. In order to explain these phenomena we make hypotheses concerning the structure of the inside of the watch. We imagine various arrangements of springs, wheels, and levers till we hit on one particular system which consideration shows us will give the observed result. Here we have an intimate picture of the inside of the watch, which may or may not represent the only possible arrangement, and may or may not correspond with the reality. Such a picture is analogous to a molecular theory of a physical problem.

One day, however, we notice, in the course of our studies of the watch, that, whatever be the position of the hands, one of them always moves twelve times as fast as the other. We have discovered a necessary relation between the phenomena, which enables us, if we will, to dispense with all hypotheses about the wheels and springs which drive the mechanism. The observed connection between the rates of motion allows us to evade all such complications, and to calculate directly the relative positions of the two hands at any future time.

So with thermodynamics. Lord Kelvin's great principle of the dissipation of energy, especially in its modern form, which states that the available

energy of an isothermal system tends constantly to decrease, enables us in many cases to evade all molecular considerations, and to trace directly the connections between various physical and chemical phenomena. By this method it is possible to develop the theoretical relations of many subjects without involving the molecular hypothesis. Such treatment, using as its sole principle of co-ordination the law of available energy, ultimately rests on the experimental impossibility of perpetual motion.

This way of treating physical science was at one time adopted by a certain number of chemists, as a means of presenting their subject without applying to it the language or conceptions of the atomic theory, in terms of which even its simplest experimental facts have come to be expressed. In particular Franz Wald and Ostwald have explained the phenomena of chemical combination in definite proportions from the standpoint of energetics. They have shown that the existence of the two types known to us as elements and compounds may be deduced from the thermodynamic theory of equilibrium without reference to atomic hypotheses. But, in the present state of knowledge, such a doctrine seems limited in its scope, and cases in which it ceases to be sufficient will constantly recur in this volume. For instance, the phenomena of highly rarified gases have only been interpreted successfully by the aid of strictly molecular conceptions. The passage of electricity through gases, which will be considered in a future chapter, again suggests molecular hypotheses, and, in conjunction with the phenomena of radio-activity, gives an extended

insight into the intimate structure of atoms and molecules. In such matters we are driven back to molecular theory, which offers an alternative method of correlating other phenomena also, equally definite, and supported by an ever increasing number of experimental concordances.

Thermodynamic theory, as well as practical experiment, thus indicates that the osmotic pressure of a solution depends only on the number of dissolved particles, and not on their nature or on the nature of the solvent. The phenomena of gases show that the number of molecules in two systems may be compared by a knowledge of the total masses and of the chemical molecular weights. Thus, two solutions, one of sugar, let us suppose, and one of alcohol, which are prepared so as to contain the same number of molecules in the same volume, both in theory and practice, possess equal osmotic pressures. But, if equimolecular solutions of sugar and salt be examined, the osmotic pressure of the salt is found to be greater, and, if the solutions be dilute, nearly twice as great as that of the sugar. These abnormally great osmotic pressures were discovered at an early date in the history of the subject; and further investigation showed that, at all events when the solvent was water, they occurred in the cases of those solutions which were conductors of electricity.

When Van't Hoff formulated the physical theory of the osmotic pressure, he treated these abnormal values as exceptions to the usual law. It was reserved for the physicists Arrhenius of Stockholm and Planck of Berlin to point out

that the extension of Van't Hoff's principles to these cases required the assumption of the dissociation of the molecules of salt in order that the total number of particles in solution should still be the number indicated by the observed phenomena. According to this hypothesis, in a dilute solution of common salt, the solute does not exist as molecules of sodium chloride, but as the dissociated parts, sodium and chlorine, which, since the solution conducts a current of electricity, must be associated with electric charges. Each salt molecule thus gives two pressure-producing particles in solution, and the double value of the osmotic pressure is explained. In stronger solutions this dissociation is not complete, and the osmotic pressure is less than twice the normal value; but no exact correlation of pressure and dissociation can be made, for the thermodynamic theory as formulated above is only valid for very dilute solutions.

Like the thermodynamic theory of osmotic pressure generally, this extension of it does not involve any particular view as to the cause of the pressure or the nature of solution. The dissociation hypothesis is concerned simply with the difference between solutions of electrolytes and non-electrolytes, and leaves entirely open the more fundamental question, whether solution is essentially chemical or physical in its nature.

The dissociation theory of aqueous solutions of electrolytes, originally indicated by osmotic phenomena, is supported perhaps even more clearly and strongly, by the study of the electrical properties. During the years 1830 to 1840,

Faraday made a series of experiments on the passage of electricity through liquids, in this way laying the foundations of our quantitative knowledge of that subject. He showed that the transfer of a given quantity of electricity was always accompanied by the liberation of a definite quantity of one of the constituents of the solution, a quantity proportional to the total electric transfer, and to the chemical equivalent weight of the substance liberated. The quantity of electricity which passed, then, depended on the number of chemical equivalents of substance liberated, and not on their nature. These results led to a definite view as to the nature of the process of electrolysis. We must regard the passage of an electric current through a solution as due to the carriage by moving parts of the salt of opposite electric charges in opposite directions through the liquid. Under the influence of applied electric forces, these carriers drift through the solution, and finally give up their charges to the electrodes, as the terminals by which the current enters and leaves the solution are called. With common salt, for example, a stream of positively electrified sodium drifts with the electric current, while negatively electrified chlorine passes in the opposite direction. The moving parts of the salt, with their accompanying electric charges, were named ions by Faraday; the positive ion which moves down the electric current is termed the cation, and the negative ion which travels up the electric stream is called the anion. The electrodes to which they travel are known as the cathode and anode respectively. The electric charge on a single ion of a substance like sodium

or chlorine constitutes a true natural unit of electricity. No smaller quantity seems capable of existing. As Helmholtz has insisted, electricity, like matter, is not infinitely divisible ; it possesses an atomic structure.

In the year 1855 Hittorf examined the changes in the concentration of a solution which occur on the passage of an electric current, and explained them by supposing that the two ions moved at unequal rates. It is evident that more salt will be taken from that end of the solution from which comes the more mobile ion, and, on the assumption that this is the only cause at work, Hittorf calculated the ratio between the velocities of the two ions in many cases.

The next great step was made by Kohlrausch, in 1873. The conductivity of a solution is measured by the total quantity of electricity which passes through the solution per second under the action of a given electric force ; and, since the current is carried by the motion of charged ions, the conductivity must depend on the number of the ions, that is, on the concentration of the solution, and on the velocity with which the opposite ions move through the liquid. Thus, by measuring the conductivity, the velocities of the ions under a given electric force can be calculated.

So far the movement of the ions was visible to the mind's eye only. Their passage through a solution seemed necessary to explain the facts, and, in an indirect way, their velocities could be calculated, but no direct evidence of the reality of these hypothetical phenomena was forthcoming. However, in the year 1886 Sir Oliver Lodge,

and shortly afterwards by a somewhat different method the present writer, showed how to render these molecular processes visible, and how to watch the motion of the ions as they drift through the solution under the action of the electric forces.

One apparatus, as improved by Nernst, for this purpose is represented in Fig. 26. Let the solution of a colourless salt be first placed in the tube and a heavier coloured solution then run in below, so that a fairly sharp line of demarcation is produced between them. The solutions should be of the same molecular concentration, the same conductivity, and the denser solution must, of course, be placed below the lighter. Let us take, as an example, the case of solutions of potassium bichromate and potassium carbonate, which fulfil the necessary conditions. The colour of the former salt is due to the acid part, the bichromate ion, which has the chemical composition represented by Cr_2O_7 ; the potassium ion is colourless. When a current of electricity is passed across the junction between the liquids, the colour boundary is seen to move, and, from the rate at which it creeps along the tube, the velocity of the bichromate ion under a given electric force can be determined.

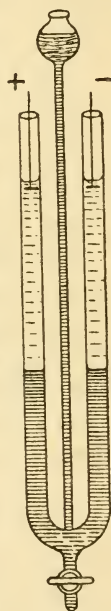


FIG. 26.

The conductivity of a salt solution, made solid by the addition of gelatine or some similar substance, is nearly the same as that of the liquid solution without the jelly, and this fact

justifies the use of such solid solutions in experiments on the migration of ions. Lodge determined the velocity of the hydrogen ion by watching the rate at which, passing along a glass tube, it changed the colour of an indicator, while the present writer has measured the velocity of many other ions by tracing the formation of opaque precipitates, formed in minute quantity by the ions in their path.

These methods have been improved and extended by Orme-Masson, B. D. Steele, G. N. Lewis, and Lash Miller. The result of the experiments is to confirm the values for the ionic velocities calculated from the theories of Kohlrausch and Hittorf.

The velocities with which the ions travel, even when driven forward by intense electric forces, are very small. Hydrogen, the most mobile ion known, moves over a distance of 10 centimetres, or 4 inches, in one hour, when the applied electromotive force is 1 volt per centimetre. Most other ions travel at about one-tenth this rate.

These comparatively small velocities must not be confounded with an entirely different thing: the velocity with which an electric impulse, started at one end of a tube filled with an electrolyte, reaches the other end. This velocity is very great, closely approaching the rate at which an electro-magnetic wave travels through free space, that is, the velocity of light, about 180,000 miles a second.

If we accept for the moment the common conception of an electric current as analogous to the flow of a liquid through a conducting pipe, the

connection between the two modes of motion may be illustrated by a familiar example. Suppose that a long wooden rod is lying on the surface of the ground, and that a push is given to one end of it. The motion of the rod may be quite slow, an inch an hour if we like. But, after moving one end, the other end begins to move an extremely minute fraction of a second after the starting of the impulse. Perhaps it never has occurred to us that any appreciable time elapses between the starting of the two ends. Yet, if we think for a moment, it is clear that the initial push must travel as a wave of compression along the rod, and that the far end can only begin to move when the wave front reaches it. The bearing of the analogy is now obvious. The slow movement of the rod as a whole when once started corresponds with the slow drift of the ions; the almost instantaneous passage of the wave of compression along the rod corresponds with the velocity of electricity in the electrolytic solution.

A picture of the phenomena, more nearly corresponding with the facts, is obtained by considering that the rapid electric impulse travels as an electric wave through the surrounding insulating medium. On this view, due to Faraday and Maxwell, and now universally accepted, the electric forces always travel through the medium. When they act on electric charges free to move, as in metallic conductors, or on charges attached to matter as in electrolytic solutions, they produce a drift of the charges—a drift which constitutes a current. Along the line of the drift, that is, along a conductor, energy is lost, and thus along that line, and there alone, energy is constantly flowing,

being carried forward by the medium to supply the place of the energy dissipated by the current.

The mobility of any one ion is, in dilute solutions, independent of the nature of the other ion present, at all events in simple salts, such as the chlorides of sodium, potassium, and lithium. This independence itself indicates that the ions are free from each other, and again suggests some form of dissociation.

The phenomena of conductivity also point to the same idea. To set free an ion or its products at the electrodes requires the expenditure of a certain amount of electric work, and at the electrodes an equivalent reverse electro-motive force exists. When, however, this reverse force is overcome, the passage of the current through the solution is opposed by no other reversible forces, and it is found that the work expended is that required to force the current against the frictional resistance of the electrolyte alone. The current is proportional to the excess of the electric force applied beyond what is needed to overcome the effect at the electrodes; this part of the conduction conforms to Ohm's law, which describes the process in metallic conductors. In the body of the solution, then, as distinct from the transition layer in contact with the electrodes, the electric forces do no reversible work, such as would be needed to separate the ions from each other. Whatever freedom is requisite between the ions for the purpose of conduction, must necessarily exist whether the electric forces act or not; the function of the electric forces when applied is simply to force the ions, already separated from

each other, against the frictional resistance of the liquid medium. A certain freedom of interchange, at all events, is thus indicated between the ions, and the freedom of interchange exists whether the current passes or not. Such freedom, indeed, had been inferred long ago from the phenomena of double decomposition observed in the chemical reactions between solutions of different salts.

So far the conductivity relations indicate the possibility of ionic interchange between the parts of the dissolved molecules, though the conformity of solutions with Ohm's law does not, of itself, necessitate the idea of permanent ionic freedom. But on any other view the possibility of interchange must be secured by collisions between the dissolved molecules, and consequent interchanges between their ions, which would thus work their way through the solution by a series of such collisions. The velocity with which this process is effected must depend on the frequency of collision, which would be proportional to the square of the concentration. The ionic velocities, then, on this supposition, would increase in proportion to the square of the concentration of the solution, and the conductivity, which depends on the product of the ionic velocities and the concentration, would vary as the cube or third power of the concentration.

But the facts are quite inconsistent with this hypothesis. The conductivity is proportional at the most to the first power of the concentration; and the ionic velocities, instead of increasing as the square, are, in dilute solution, independent of the concentration, and in more concentrated solutions decrease with increasing concentration. Thus again we are driven to the belief that the

ions are free from each other, and move independently of each other through the liquid under an electric force: free from union with each other, let us observe, not necessarily free from combination, chemical or other, with the solvent. As already indicated, the dissociation theory does not depend on any particular view as to the nature of solution in general.

For aqueous solutions, then, the evidence in favour of the dissociation hypothesis is very strong, and it can safely be used as a working hypothesis to co-ordinate the known phenomena, and to guide future research. For solutions in other solvents, less evidence is yet available; though for solutions of certain salts in alcohol, the laws of the electrolysis seem to be similar to those of aqueous solutions and to indicate a similar theory. In fused salts, which also conduct electricity and suffer chemical decomposition at the electrodes, the conditions are perhaps different, and we must wait for further light before we can profitably theorise about the nature of the conduction process.

Besides explaining the electrical and osmotic properties of solutions, the dissociation theory, in the domain of chemistry, has proved one of the most fruitful generalisations that has ever been formulated. Solutions of salts and acids, electrolytes in fact, are the solutions which exhibit chemical activity in the highest degree. In them, the ions alone are concerned in chemical action, and so clearly is this the case, that, as soon as the subject is examined, the ordinary chemical tests for the presence of salts are seen

at once to be, in reality, tests for the individual ions of those salts. At one time it seemed likely that all cases of rapid chemical action might be reduced to reactions between electrolytic ions, but experiments by Kahlenberg and others seem to show that in non-aqueous solvents rapid reactions may occur not in any way correlated with electrolytic conductivity. However this may be, in water many chemical actions are certainly connected in a very intimate way with the electrical properties, and the dissociation theory gives a satisfactory method of co-ordinating the two sets of properties. In some reactions the actual electric charges on the ions seem to be the determining factors of the whole process.

There is a marked difference in chemical and physical properties between bodies of definite crystalline form, such as most inorganic salts, and soft or amorphous substances, such as albumen and the various kinds of jelly. Long ago Graham distinguished the two groups as crystalloids and colloids respectively, and particularly examined them with regard to their relative powers of diffusion through water. He found that, while crystalloids diffuse comparatively rapidly, the motion of colloids is so slow that it is often almost inappreciable.

Many different kinds of chemical compounds show colloidal properties. Besides a vast number of animal and vegetable substances, some of which are of fundamental importance in the phenomena of living matter, many of the precipitates which are formed in the course of inorganic chemical reactions appear in an amorphous or colloidal state. The sulphides of such metals as antimony

and arsenic are good examples. If a solution of arsenious acid be allowed to flow into water kept saturated with sulphuretted hydrogen by means of a current of that gas, a colloidal hydrosulphide is formed. Many hydrates, too, are colloids, ferric hydrate, for instance, which can readily be prepared from the corresponding salts of iron. By treating dilute solutions of gold chloride with reducing agents, such as a few drops of a solution of phosphorus in ether, the gold is set free in the colloidal condition, forming a ruby-coloured solution. Silver, bismuth, and mercury can also be obtained in colloidal solution.

Crystalloids diffuse much more rapidly through water and other solvents than do colloids. If a mixture of crystalloids and colloids be placed in a drum covered with a colloidal membrane, such as bladder or parchment, complete separation can be effected, for the dissolved colloids seem quite incapable of passing through such membranes. This process probably plays a great part in animal and vegetable physiology.

Solutions of colloids in crystalloid solvents, such as water or alcohol, seem to be divisible into two classes. Both classes appear to mix with warm water in all proportions, and the mass will solidify under certain conditions to form a solid which may be called a gel. One class, represented by gelatine and agar jelly, will, when solidified, redissolve on warming or dilution, while the other class, containing such substances as hydrated silica, albumen, and metallic hydro-sulphides, will, under the influence of heat or on the addition of electrolytes, form gels which cannot be redissolved. The solidification of members of the first class into

redissolvable substances is termed setting, that of substances in the second class, which form insoluble precipitates, is termed coagulation.

The mechanism of gelation in the first, or reversible class of colloidal systems, has been studied experimentally by Van Bemmelen and by W. B. Hardy. The process of solidification seems to consist in the growth of a solid framework containing more liquid portions. The temperature at which this separation into two phases occurs depends on the amount of water present.

The coagulation of irreversible colloidal solutions, as already stated, can be effected by the addition of small quantities of the solution of an electrolyte, such as an ordinary salt or acid. Graham, who originally investigated the subject, found that a minute trace of salt was often sufficient. Thus, hydrated alumina, prepared from a solution of the chloride in distilled water, was so unstable that a few drops of well-water produced coagulation, and the same change was brought about by pouring the colloidal solution into a new glass vessel, unless the vessel had previously been washed repeatedly with distilled water.

Several experimenters, including Schulze, Linder and Picton, and Hardy, have investigated this coagulative power of electrolytes, with very curious and interesting results. The coagulative power of a salt is found to vary in a remarkable manner with the chemical valency of one of its ions.¹ The average of the coagulative powers of

¹ The valency of a chemical atom may be defined as the number of hydrogen atoms it will combine with or replace. Thus the normal valency of oxygen is two, since two hydrogen atoms unite with one oxygen atom to form water. Faraday's work showed that the electric charge carried by an ion is proportional to its valency.

salts of univalent, divalent, and trivalent metals were found to be proportional to the numbers 1 : 35 : 1023 respectively. Most properties which depend on the valency vary in the ratios 1 : 2 : 3, and the great difference in the numbers now under consideration is very striking. An attempt at a preliminary explanation of these unusual relations has been made by the present writer.

Let us frame a mental picture of a solution as it is represented by the dissociation theory. A certain number of the dissolved molecules are regarded as dissociated into charged ions, which wander, free from each other, through the liquid, perhaps by successive combinations with solvent molecules in their path. When an electric force is applied, though still moving sometimes in one direction and sometimes in another, the ions, on the whole, drift in the direction indicated by the force, and we may imagine, therefore, that two processions of oppositely charged ions pass each other, drifting in opposite directions through the solution.

When there is no electric force, the ions are subject to no steady drift, and must move sometimes in one direction, sometimes in another, as the chances of their life direct. Any one ion will be passing sometimes from one solvent molecule to another, carrying its electric charge with it; sometimes it will come across an ion of the opposite kind in such a way that combination occurs, and, for a time, an electrically neutral molecule is formed. By collisions of unusual violence, or by other means, soon this molecule will be dissociated, and its ions again set free from each other, to be handed backwards and forwards by the solvent molecules as already described.

Let us suppose that, in order to produce the aggregation of colloidal particles which constitute coagulation, a certain minimum electric charge has to be brought within reach of a colloidal group, and that such conjunctions must occur with a certain minimum frequency throughout the solution. Since the electric charge on an ion is proportional to its valency, we shall get equal charges by the conjunction of $2n$ triads, $3n$ diads, or $6n$ monads, where n is any whole number.

The chance conjunctions of a large number of particles moving like the ions of an electrolytic solution can be investigated by the principles of the kinetic theory of gases. If $1/x$ denote the chance of one ion colliding with a colloidal particle, the chance that two ions should collide with it is the product of their separate chances, or $1/x^2$, and so on. When applied to the case in hand, these principles lead to the conclusion that the relative coagulative powers of univalent, divalent, and trivalent ions will be proportional to the ratios $1 : n : n^2$. The value of n , which depends on a number of unknown factors, remains arbitrary. If we assume that n is 32, n^2 is 1024, and we get the numbers $1 : 32 : 1024$ to compare with the experimental values of the relative coagulative powers $1 : 35 : 1023$.

This theory is, of course, only a first approximation. It takes no account of the action of the other ion, or of differences in the effect of different ions of the same valency. Experiments by Oden on colloidal sulphur show these differences to a degree that in some instances masks the effect of valency. But this extreme specific effect has not been found in any other case, and it seems that the simple theory

given above supplies a foundation on which a more detailed explanation may some day be built.

The particles in solutions of colloids in water generally move slowly when acted on by electric forces, the direction of motion depending on the nature of the colloid and on that of the solvent. Hardy found that the direction of movement of certain proteins could be changed by changing the solvent from a very dilute acid to a very dilute alkali. This reversal implied a change in the sign of the charges on the colloid particles; and, if the solvent was very carefully neutralised, an isoelectric point was reached at which the solution became very unstable, and coagulation seemed to occur spontaneously. The same observer also found that, in the case of colloids travelling with the current, it is the acid ion which is active in causing coagulation, and not the metallic ion as in the work of the older experimenters, who all used colloids which travel against the electric current. Thus it is always the ion possessing a charge of opposite kind to that on the colloid particle which is effective in producing coagulation.

Burton has found a similar change in velocity in an electric field when to a colloidal solution of silver increasing amounts of aluminium sulphate are added. The velocity of the silver decreases, and vanishes at or near the coagulating point. With more aluminium, coagulation is prevented for a time, and the unstable colloid moves in the opposite direction, showing that its electric charge has been reversed by the absorption of excess of aluminium ions.

These results are of great importance from the point of view of physiology, and also as

throwing light on the nature of colloid solution—perhaps, indeed, of solution in general. It looks as though colloid particles, at any rate, could exist in solution only when charged electrically. If, by the conjunction of more mobile ions, their charge is neutralised, or perhaps reduced to a critical value, an iso-electric point is reached, and coagulation must immediately follow.

It is probable that these effects depend on changes in the surface of separation between the colloidal particles and the more liquid phase which surrounds them. Such a surface of separation must exhibit the well-known phenomena of surface-tension, and will possess an amount of available energy proportional to its area, which therefore tends to become as small as possible. A number of separate particles would, in these conditions, tend to coagulate into larger ones, just as small raindrops tend to coalesce into larger ones. If the colloidal particles are electrified, the electric energy is greater when the charge is concentrated on a small area, and, on this account, the area will tend to increase. The effect of the electric charge is thus opposite to that of the natural surface-tension, and diminishes the tendency to coagulate. Thus an electric charge may enable the colloid to dissolve, while neutralisation of the charge may result in coagulation.

Much discussion has taken place about the nature of liquid colloidal solutions, and their relations with ordinary solutions of mineral salts and other crystalloids. They may either be regarded as ordinary solutions, in which the dissolved particles are similar in kind to those of crystalloid solutions, though of much higher

molecular weight, or they may be considered to be systems of two phases, composed of suspensions of particles in the liquid, the particles being different in kind from the liquid, and of much greater than molecular dimensions.

In some colloid solutions the presence of suspended particles can be detected readily by ordinary means. Sometimes they are visible under a good microscope; in other cases, while too small to be directly visible, they are large enough to scatter and polarise a beam of light. This means that their size must be comparable with the wave-length of light, about 5×10^{-5} cm. Such particles would be too few in number to exert a measurable osmotic pressure, and the absence of such pressure does not necessarily mean that solutions of colloids are different in kind from solutions of crystalloids.

It is worthy of note that turbid suspensions of clay, kaolin, etc., in water are rapidly cleared by the addition of small quantities of metallic salts. This action, which is almost certainly of the same nature as the coagulation described above, probably helps in the formation of sand-banks at the mouths of rivers; the salts of the sea-water clear the suspensions of clay brought down with the fresh water, and precipitation is then aided by the diminished velocity.

The conditions which determine the colloid or crystalloid nature of a substance are still not fully understood. The persistence of colloid properties, when a substance passes from the dissolved to the non-dissolved state, shows that the determining conditions must be of fundamental importance. The molecular forces seem to be much less active in colloids, but the freedom with which some of

them disintegrate and dissolve in presence of water and other liquids indicates that some interaction between them and their solvent must occur. It seems likely that the forces which are involved in crystalloid solution are of the nature of those classed as chemical or molecular, while, when colloids dissolve, the actions between solvent and solute are conditioned also by the phenomena studied under the names of capillarity and surface tension. It is not likely that any sharp line of demarcation can be drawn; though, as the size of the dissolved particles increases, the importance of the chemical forces probably diminishes, and that of the capillary forces grows.

If colloid and crystalloid solution are but the extreme limits of a continuous series of phenomena, the study of dissolved colloids of varying degrees of aggregation should throw much light on the general problem of the fundamental nature of solution.

A study of the colloidal state is primarily the affair of physics and chemistry. But that study has led to many technical applications, as, for instance, in dyeing, of great industrial importance. Moreover, colloids play a supreme part in the phenomena of living matter. Protoplasm, the material basis of life which fills all living cells, is essentially a colloid, and in physiology and biochemistry colloidal problems continually arise. Again, the soil of our fields, so simple to the eyes of the pioneers in agricultural chemistry, is now known to be a complex containing many colloids, with a flora and fauna of its own. But this is not the place to follow further these fascinating developments—the physics of colloids contains enough of interest.

The explanation of the coagulation of colloidal solutions as an effect on the surface conditions at the junction between colloid and solvent, brought about by the chance conjunctions of dissociated electric ions, is an illustration of a course of history which indeed constantly repeats itself in scientific inquiry. An observation is made, perhaps long series of experiments are carried out, before the general state of knowledge enables a satisfactory explanation of the phenomena to be formed, or a theoretical co-ordination of them with other phenomena to be traced. Even Graham's acute and powerful mind, in the absence of the dissociation theory of electrolytes, and of the knowledge of the surface relations of two phases which we now possess, could frame no explanation of the coagulation effects which he examined with such skill. By experiments on coagulation alone it is probable that an explanation could never have been reached. But by the advance of other observers, led by Gibbs on one far-off flank, and by Van't Hoff and Arrhenius on the other, almost out of touch with the original attack, the position of the adversary—ignorance—was turned; and when, at a later time, a new frontal assault was made, the way lay open to an approximate theory, and probably in the future will lead to a complete explanation.

For, while the tired waves, vainly breaking,
Seem here no painful inch to gain,
Far back, through creeks and inlets making,
Comes, silent, flooding in, the main.

And not by eastern windows only,
When daylight comes, comes in the light;
In front the Sun climbs slow, how slowly!
But westward, look! the land is bright.



J. J. Thomson

CHAPTER VI

THE CONDUCTION OF ELECTRICITY THROUGH GASES

“It is difficult to think of a single branch of the physical sciences in which these advances are not of fundamental importance. . . . The physicist sees the relations between electricity and matter laid bare in a manner hardly hoped for hitherto. . . . But it is the philosopher that these researches will affect most profoundly. As much by the aid of a perfect mastery over the properties of materials as by the sheer intellectual power of abstract reasoning, some of the fundamental problems of the constitution of matter are here presented as on the verge of solution.”—*Times*, 22nd January 1904.

UNLIKE the liquid solutions and other electrolytes studied in the last chapter, gases, in normal conditions, are almost perfect insulators of electricity. Telegraph wires are insulated by the air which surrounds them, and, if leakage occurs to any measurable extent, it can always be traced to the solid supports to which the wires are attached. Nevertheless, by delicate instruments, a slight leakage of electricity through air can be detected. This air leakage is usually extremely small, but it can be increased greatly in many ways. The passage of Röntgen rays, the incidence of ultra-violet light on a metal plate, the neighbourhood of flames, incandescent metals, or of radio-active bodies such as radium, are among the agencies whereby the condition of the surrounding air is modified so that it can rapidly conduct away the electric charge.

In general, the currents through gases are too

small to be investigated by means of a galvanometer. By the aid of an electrometer, however, or by the use of some form of gold leaf electroscope, the passage of electricity may be detected, and the amount of the current determined.

The quadrant electrometer consists of a light but rigid strip of aluminium or silvered paper, suspended horizontally by a fine quartz fibre. This strip is kept permanently charged with electricity, and is therefore deflected when other charges are given to brass quadrants which surround it. By the rate at which the deflection diminishes, it is possible to estimate the rate at which the charge on the quadrants, and on any conductor connected with them, disappears or increases.

Still simpler and yet more sensitive is the gold leaf electroscope, in which a thin strip of gold leaf is attached to a brass plate, and charged with electricity. Owing to the repulsive forces between portions of the same charge, the gold leaf is repelled from the plate and stands out at an angle. By observing through a microscope the rate at which the leaf falls, we can determine the rate at which its charge leaks away.

Whichever apparatus be adopted, the natural leak, due to the apparatus itself and the air surrounding it, must first be determined, and subtracted from the leakage afterwards found under the influence of an ionizing agency.

In the last chapter we have seen that the properties of conducting solutions have been successfully co-ordinated and explained on the hypothesis that the passage of a current is effected by the motion of charged particles called ions.

A similar supposition has been adopted to explain the conductivity of gases, although it will be clear that, in many respects, the ions in the case of electric discharge through gases must be endowed with properties different from those which pertain to the ions of liquid solutions.

After a period of activity on the part of some ionizing agency, such as Röntgen rays, the resultant conductivity does not cease simultaneously with the action of the rays. It persists for some little time; it can be blown about with currents of air; and in all respects acts as though it were due to the presence of material particles, formed somehow in the gas through which the rays had passed. The conductivity is destroyed if the gas be passed through a plug of glass wool or bubbled through water; it is also removed if the gas be subjected to the action of an electric field. Such experiments, and many others of somewhat similar nature, are readily explained by the conception of charged particles, which, produced in some way by the action of the ionizing agency on the molecules of the gas, are afterwards driven through the gas by an electric force, just as the ions of a salt solution are driven through the liquid. Unlike the ions of liquids, however, those of gases do not long persist after the cessation of the outside ionizing agency. Left to themselves, the ions gradually disappear. Such a disappearance might be anticipated on the view that the opposite ions recombine and neutralise each other, and also on the assumption that they give up their charges to the solid objects with which they come in contact as they move about under their own motions of diffusion, and

that they are driven towards an electrode by the action of an electric force.

The non-persistence of gaseous ions and the consequent need of their perpetual renewal explains the relation between current and electro-motive force—a relation different from that observed in liquid solutions. In solutions, as we saw, the conduction conforms to Ohm's law—the current is proportional to the electro-motive force. In

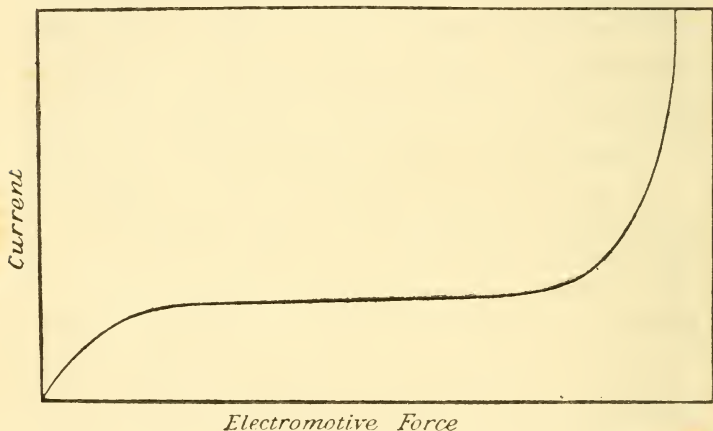


FIG. 27.

gases this is not the case. For an ionizing agency of constant intensity, such as a layer of oxide of uranium, the current at first rises with the applied electro-motive force, but soon it tends towards a limit, and finally reaches a maximum, when, till we approach the sparking point, no further increase of electro-motive force will produce any appreciable increase of current. This saturation current, as it is called, is represented by the horizontal part of the curve in Fig. 27. Obviously it corresponds

to a state in which all the ions are removed to the electrodes as fast as they are produced by the ionizing agency.

As the sparking point is approached, the curve shows that the current again rises rapidly; the applied electric force being strong enough to produce ions in the gas by its own action. Townsend has shown that this process is effected by the collision with the gas molecules of ions already present, which are driven forward by the electric force with high velocity. In this way are formed most of the ions which carry the current in an electric spark, or in the arc discharge.

We have described already the methods of calculating the velocities with which the ions of liquids move under known electric forces, and of determining those velocities by direct experiment. For gaseous ions, the corresponding velocities are much higher. They have been determined in several indirect ways, with concordant results. For instance, Zeleny measured the electric force required to push an ion against a stream of gas, moving with a known and uniform velocity in the opposite direction to the natural motion of the ion. Langevin, in 1902, attacked the problem in another way. The gas between two parallel electrodes was exposed momentarily to the action of Röntgen rays. The ions thus produced may disappear in two ways. Opposite ions may recombine with each other, or they may pass to the electrodes under the influence of an electric force. If the force be great, the latter method alone is operative, the number of ions recombining before reaching the electrodes being very small. If, then, the

electric field be kept acting in one direction, all the positive ions produced by the Röntgen rays will go to one electrode, and all the negative ions to the other. But if the electric force be reversed before all the ions get across, the charge received by an electrode would be less than before. Thus, measurement of the charges received by the electrodes with different speeds of reversal will give a means of calculating the velocities of the ions. At atmospheric pressure, under a potential gradient of 1 volt per centimetre, the velocities of different ions vary from about three-quarters of a centimetre per second in the case of carbon dioxide, to about 7 centimetres per second in the case of hydrogen. The velocity of the negative ion is, in general, appreciably greater than that of the positive ion, the ratio, unity for carbon dioxide, rising to 1.24 for air and oxygen.

We should expect the velocity of an ion to be inversely proportional to the pressure of the gas, and this has been found to be the case with the positive ions. The mobility of the negative ions, on the other hand, increases with decreasing pressure much faster than this expectation justifies, and at low pressures, 100 millimetres of mercury and less, the change is very marked. This result indicates an alteration in the nature of the ions themselves, and justifies the belief that they must possess more complex structures at high than at low pressures.

We shall see later that, at the very low pressures which exist in good vacuum tubes, it is possible to estimate the absolute mass of the ions, with the remarkable result that, whereas the mass of the positive ion appears to be much

the same as the mass of an atom, the mass of the negative ion is about the eighteen hundredth part of the mass of the lightest atom known to chemistry, that of hydrogen. The decrease of the ionic velocity at low pressures probably indicates an approach to this state of low ionic mass.

A similar decrease in the size of the negative ion, compared with that of the positive, is produced by raising the temperature. H. A. Wilson found that, at 2000°C ., the velocity of the negative ions, produced by salts volatilised in flames, was seventeen times greater than the velocity of the positive ions.

The problem of determining the dimensions of the ions at atmospheric pressure has been attacked by measuring their rates of diffusion into non-ionized gases. The rate of diffusion of a gas depends on the mass of its molecule, and experiments show that the mass of an ion at atmospheric pressure is considerably greater than that of the molecule of an ordinary gas.

All these results may be explained by the theory that the normal process of gaseous ionization consists in the detachment from an atom of the gas of a minute particle, called by Sir J. J. Thomson a corpuscle. At extremely low pressures the corpuscle constitutes the negative ion, and the atom or molecule from which it has been separated forms the positive ion. As the pressure rises, neutral molecules become attached to the ions, probably by virtue of the electric forces, and collect round the original ion, which constitutes the nucleus. These complex systems form the ions of gases at atmospheric pressures.

The presence of gaseous ions may be inferred from the phenomena of current conduction through the gases, but the existence of charged particles of greater than molecular dimensions has been demonstrated directly by Mr C. T. R. Wilson in a very striking manner. Long ago Aitken showed that the condensation of drops of water from air saturated with aqueous vapour was much helped by the presence of particles of dust; in the absence of dust, considerable supersaturation could be attained before condensation set in. Each particle of dust forms a nucleus, round which collect molecules of water; and, when the drops have grown to a sufficient size, they fall, carrying down the dust particle also. In this way the air is freed from the presence of dust, and to this action, on a large scale, we must attribute partially the clearness of the atmosphere after a downfall of rain.

Wilson devised an apparatus whereby air could be subjected to a sudden expansion. By this means it was cooled; and, if previously saturated with water vapour, any desired degree of supersaturation could be obtained by adjusting the amount of expansion. By repeated expansions, the dust particles were removed, and any further expansion then produced only a few drops of water. If, however, when the air had thus been depleted of possible nuclei, Röntgen rays or other ionizing agency were allowed to act on the gas, instead of these few drops, a dense cloud was once more obtained by the same expansion. This cloud was not formed if the ions were removed previously by an electric field, or by some other means.

Fig. 28 is a photograph of one of Mr Wilson's

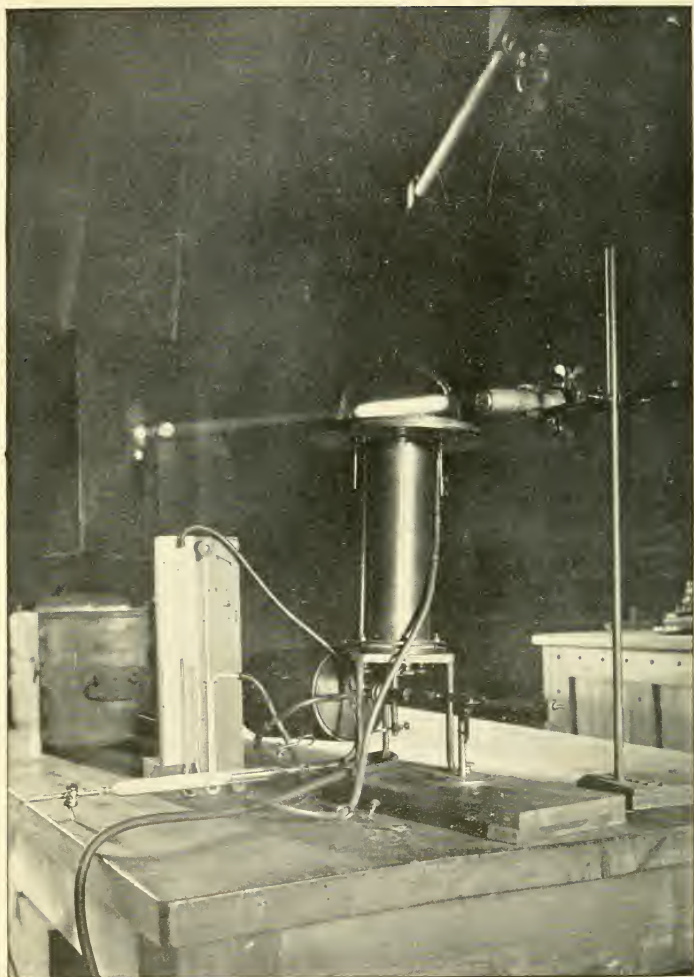


FIG. 28.—CONDENSATION OF CLOUD ON GASEOUS IONS
(*Mr C. T. R. Wilson*).

clouds, illuminated by a beam of light from an electric lantern. The nuclei in this case were the ions produced by a piece of radium contained in the tube seen to the right of the glass cloud-chamber. The cloud has settled down to the lower part of the hemispherical chamber, and its sharply-defined upper surface is clearly visible. The expansion is effected by the movement of a piston within the vertical brass cylinder, the lower part of which is put suddenly into communication with the exhausted vessel seen lying on the table.

In 1893, Professor Thomson had shown that, in causing condensation, negative electrification was more effective than positive, and Wilson, in 1899, further examined this point. He found that, while negative ions produced condensation of a cloud when the volume of the gas was increased in the ratio of 1 : 1.28, positive ions did not cause an equal effect till the expansion reached 1.31. It is possible that this difference may have an important meteorological significance. If, as there is reason to suppose, the atmosphere sometimes contains a considerable number of gaseous ions, an expansion or fall of temperature would result in the formation of drops of water round the negative ions sooner than round the positive ions. The negative ions thus would be removed first, and the air would be left with an excess of positive electrification. It is not unlikely that the origin of the commonly observed potential of the atmosphere, positive relative to that of the earth, is, partially at any rate, to be found in this selective withdrawal of the negative ions.

If the ionization be not too intense, it is possible to remove completely the ions from air by means

of a single expansion. Each ion will then be the nucleus of a water-drop; and, since the amount of water left in the air must be just that required for the equilibrium of saturation, the quantity of water removed by the falling cloud can be calculated. This amount of water is constant for a given expansion, and the number of ions present must therefore be the factor which determines the size of the drops. Minute drops, the constituent parts of the artificial cloud or fog under consideration, fall very slowly, and Sir George Stokes showed long ago how their size may be calculated from the rate of their fall. The cloud settles down at a steady, well-marked pace, which can readily be observed by watching the upper surface as seen in Fig. 28. This measurement gives the average size of each drop; and, since the total mass of all the drops can be calculated from the expansion, the total number of drops, and therefore of ions, can be deduced approximately.

Sir J. J. Thomson used this method to determine the electric charge on a gaseous ion. The current through the gas is given by the product of the number of ions, the charge carried by each, and the velocity with which they move. The velocity, as we have said, can be determined for a known electro-motive force; and, by measuring the resultant current with an electrometer, and finding the number of ions by Wilson's method, the ionic charge was estimated as 3.4×10^{-10} electro-static units. Within the limits of experimental error it was found to be the same as the charge on an ion in liquid electrolysis, and this result was obtained also by Townsend in another way. The importance of this conclusion will appear later.

An electric machine capable of yielding sparks was invented many years ago during the eighteenth century; and the question soon arose whether such sparks were of the same nature as the lightning flash—whether the roll of the thunder was but the reiterated crackle of the stupendous electric machine of the atmosphere, echoing amid the convolutions of the clouds. The question was answered in the year 1752 by Franklin, who floated a kite in the air, and, when the string was made a conductor by a shower of rain, was able to draw the confirming sparks from its lower end.

A very great electric force is required to maintain a visible discharge through a few centimetres of air at the atmospheric pressure, and the initial force needed to start the process is still larger. It was soon found, however, that a reduction of pressure facilitated the passage of the spark, and that it was much easier to send the discharge through a vessel from which the air had been partially exhausted by means of an air-pump. To illustrate this, platinum wires, to act as electrodes, are sealed into little glass tubes containing air at low pressure. For many years these vacuum tubes, as they are called, were the electrical playthings of the laboratory and popular lecture-room. Recent discoveries have raised them from the position of scientific toys to the rank of pieces of apparatus, whereby have been made some of the greatest discoveries in physical knowledge that the present generation has seen.

Through such a tube, in which the pressure of the air is only a small part of an atmosphere, a discharge may readily be passed by the aid of a voltaic battery and an induction coil, or by the use

of an influence electric machine. As in liquid conductors, the electrode by which the current enters is called the anode, and that by which it leaves, the cathode. Starting from the cathode, we first see a bright glow covering its surface, then a dark space, succeeded by a second dark space, beyond which is a luminous column reaching to the anode. Within certain limits of pressure and strength of current, this positive column, as it has been called, shows fluctuating striations. If the length of the tube be increased, it is this positive column alone which increases with it; the two dark spaces, and the negative glow, vary very little with the length of the tube.

The effect of very high vacua on the electric discharge was first systematically investigated by Sir William Crookes. As the air is gradually removed, it is found that the dark space nearest the cathode, known as Crookes' dark space, gradually extends, until eventually it fills the whole tube. At this stage, green phosphorescent effects begin to appear on the anode and on the glass opposite the cathode. If a solid object, such as a screen of mica, be interposed between the glass and the cathode, a sharp shadow is seen, showing from its position that rays capable of producing phosphorescence proceed in straight lines from the cathode. These cathode rays possess momentum, for a light windmill placed in their path can be made to rotate; moreover, they are deflected by a magnet, in the same direction as would be negatively electrified particles, travelling in the course of the rays. For these reasons, the cathode rays must be regarded as a flight of negatively electrified material particles.

In the year 1895, Professor Röntgen of Munich made the first of the sensational discoveries in physical science for which the last thirty years have been remarkable. Many other recent investigations have been as interesting, and several have more profoundly modified our outlook on Nature, but few have struck so readily the imagination of the plain man as the revelation of the skeleton within the living flesh.

The origin of this discovery may be said to have been almost accidental. Röntgen noticed that photographic plates, kept under cover in the neighbourhood of a highly exhausted tube through which electric discharges were passing, became fogged, as though they had been exposed to light. He investigated this effect, and found that, when cathode rays impinged either on the glass of the tube, or on the anode, or on any metallic plate within the tube, a type of radiation was produced which would penetrate many substances opaque to ordinary light. Dense bodies, like metal or bone, absorbed the rays more fully than did lighter materials, such as leather or flesh, and Röntgen, at once putting this discovery to some purpose, was able to photograph the coins in his purse and the bones in his hand.

Given the rays, the mechanical contrivances required to demonstrate their effects are not elaborate. Röntgen rays produce phosphorescence on screens of barium platino-cyanide and other similar salts, and, by using these screens in place of a photographic plate, objects, usually hidden from our eyes, may be made visible.

A remarkable property of the rays is their power of converting the air and other gases

through which they pass into conductors of electricity. In ordinary circumstances, as was pointed out in the earlier part of this chapter, air is an almost perfect insulator; and an electrified body exposed to it, while shielded from other sources of leakage, loses its charge with extreme slowness. If, however, Röntgen rays are passing through the air in the neighbourhood of the electrified body, the charge quickly disappears.

For several years after their discovery, the physical nature of the Röntgen rays was widely discussed, and, for a long time, no general consensus of opinion was reached. Their photographic effects and the fluorescence they produced on suitable screens suggested that, like ordinary light, they were to be regarded as waves in the luminiferous æther. The power they possess of penetrating some opaque substances does not forbid such an assumption; for a difference in the wave-length, or in the period of vibration, is sufficient to produce marked differences in the penetration of ordinary light. Glass, transparent to the visible rays, is opaque to those invisible rays of longer wave-length, which possess great heating power—hence its use in fire-screens; while a solution of iodine in bisulphide of carbon is opaque to luminous radiation, but allows the long waves to pass.

Röntgen rays are not refracted like ordinary light, and very little trace of regular reflection has been detected. Moreover, it was only with great difficulty that they were persuaded to show signs of such a typical property as polarisation. Two plates of tourmaline seem to be as transparent to the rays when the axes of the crystals

are crossed as when the axes are parallel. Such indications as these did not suggest an identity in nature between Röntgen rays and ordinary light.

On the other hand, the rays suffer no deviation when acted on by a magnetic or by an electric field of force, a result which indicates that they are not projected particles carrying electric charges. In this particular, they must be distinguished carefully from their creative agency—from the flight of negative particles or cathode rays which, by impact on glass or metal, give rise to this new type of radiation.

In the year 1896, Sir George Stokes suggested that an explanation should be sought in the hypothesis that Röntgen rays were single pulses travelling through the æther. Ordinary light is to be represented as a series of regular waves, succeeding each other at periodic intervals, many thousand waves, almost exactly similar to each other, following in order in a minute fraction of a second. According to this view, Röntgen rays must be regarded as single disturbances, propagated with the same velocity as light, but not followed by a train of waves. The thickness of the pulse, in which the whole disturbance is concentrated, was supposed to be considerably smaller than the wave-length of any visible light.

But this ingenious theory of single pulses had to be discarded. Evidence accumulated that X-rays were light, of very short wave-length, and that interpretation was placed beyond doubt by Laue in 1912 and soon after by Sir William and W. L. Bragg, who showed that X-rays could be diffracted by crystals, as light is by a diffraction grating.

The usual form of diffraction grating consists of a transparent or reflecting surface, on which a large number of parallel scratches are ruled very accurately, so near together that the distance between them is comparable with the wave-length of light. By allowing light to fall on such a surface, a spectrum is formed, like that given by a prism or a rainbow. A similar effect could be obtained by a number of very thin glass plates, $p p p p$ in Fig. 29, piled closely one upon another. Let $A A' A'' A'''$ denote a wave-front of homo-

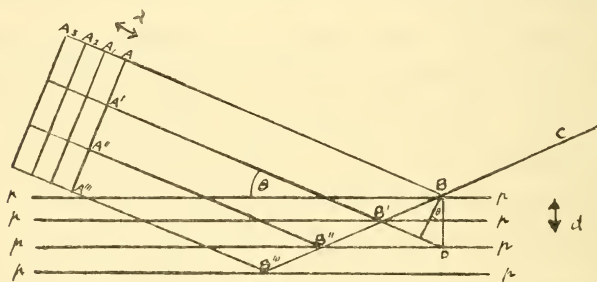


FIG. 29.

geneous light, such as the yellow rays from a colourless gas flame in which a sodium salt is placed. This light is reflected at $B B' B'' B'''$, and, in one particular direction BC , all these reflected rays coalesce. If BC is in such a direction that the difference in path between ABC and $A' B' C$ is just one wave-length, the crest of one wave will coincide with the crest of the next. All the little waves, therefore, produce similar effects, and the resultant effect is large—a bright yellow line appears along BC . Elsewhere there will be no such coincidence. Crests and troughs of the wavelets mix together, inter-

ference results, and the resultant effect is negligible. If instead of homogeneous sodium light we used white light, the different coloured components would produce bright lines at different angles, and a coloured spectrum would be formed at C at right angles to BC.

Now, if X-rays be regular wave-trains at all, their wave-lengths must be much shorter than those of visible light. No glass plates would be thin enough to give a reflection spectrum. But, if the atoms in a crystal be situated in regular layers, it is possible (1) that they might act as superposed reflecting plates, and (2) that the wave-lengths of X-rays might be of the same order of size as the distance between the layers of atoms.

This was found to be the case. In particular, the Braggs have thus proved the wave-lengths of X-rays to be about 10^{-8} , or one hundred millionth of a centimetre, and have discovered many interesting facts about the structure of crystals.

For instance, a photograph of the X-ray spectrum from a crystal of rock salt, shows that layers of high reflection are interspersed with layers of low reflection. Hence it is concluded that layers of sodium atoms lie between layers of chlorine atoms. It is the atom and not the molecule which is important in crystal structure. Indeed, the crystal must be regarded as one enormous molecule of formula Na_nCl_n .

Again, the X-ray spectrum from a diamond shows that the carbon atoms each lie at the centre of a tetrahedron, and are linked together in six-membered rings, corresponding exactly to

the ring formula of benzene which is inferred from ordinary chemical evidence.

Direct evidence of the negative charge carried by the cathode rays was given by experiments of Perrin. He showed that, when the rays were deflected by a magnet so that they fell on an insulated metal cylinder placed within the discharge-bulb and connected with an electrometer, a strong negative electrification was imparted to the system. When the rays fell on other parts of the bulb, this electrification was not observed.

A less direct but more interesting method was used by Thomson in 1897, and led to one of the great discoveries of modern science. In the glass apparatus shown in Fig. 30, the left-hand terminal of the induction coil is connected with the cathode, the right-hand terminal with a thick metallic disc which acts as the anode. Through the anode, and through a second thick disc connected with the earth by the wire going to the bottom of the photograph, are bored in sequence two holes about a millimetre in diameter. A thin pencil of cathode rays is thus obtained beyond the second disc. These rays pass between the two metallic plates, seen in the wider part of the tube, which can be connected with the poles of a voltaic battery by means of the wires passing to the right. An electric force of known amount can thus be applied to the cathode rays. When that force is sufficient, the path of the rays is deflected, and the magnitude of this effect can be determined by observing the deflection of the spot of fluorescent light on the screen at the right-hand end of the apparatus. It is well known that the cathode rays are deflected

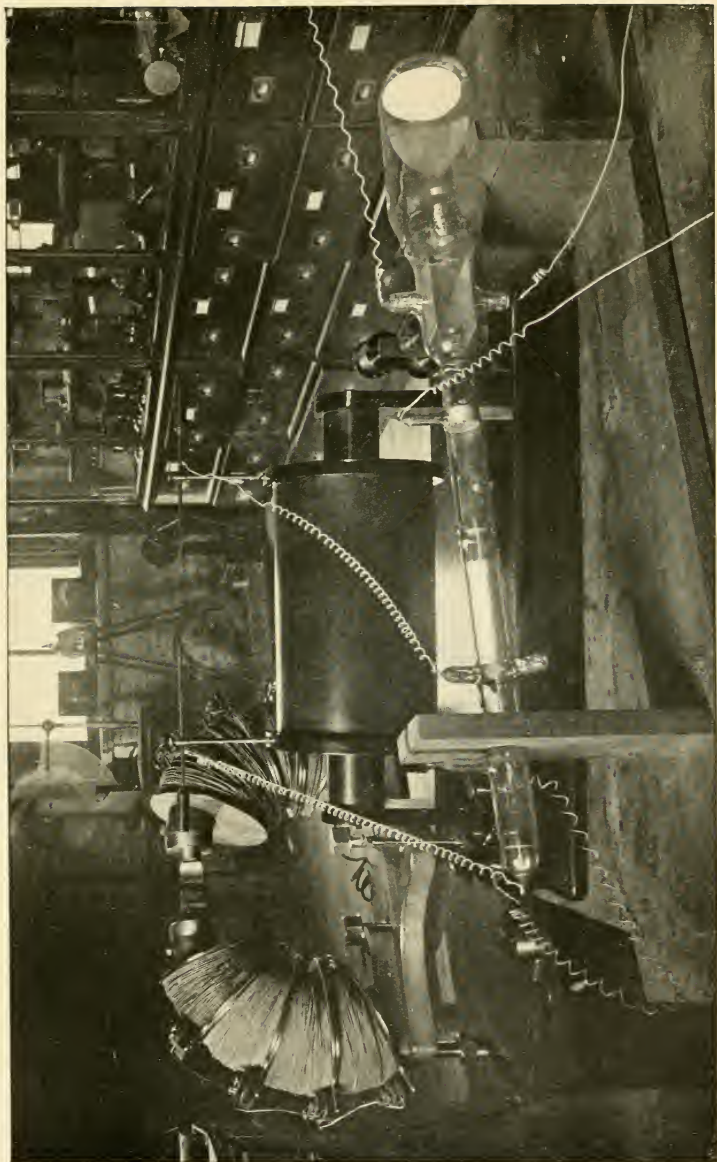


FIG. 30.—DEFLECTION-TUBE FOR CATHODE RAYS
(Professor J. J. Thomson).

by a magnetic field also, and this effect too can be measured in the same apparatus. Both these deflections are to be expected if the rays consist of moving electrified particles; and the directions of the deflections are such that the electrification must be that to which is conventionally given the negative sign.

The conclusions drawn from these experiments are of extreme importance. In analysing the deflections of the particles three things are involved: (1) the velocity; (2) the mass; and (3) the electric charge. For both deflections, the electric and magnetic, the two last quantities appear as the ratio e/m —that is, the charge divided by the mass. If we treat this ratio as a single quantity, we find ourselves with two unknown values to be determined by the two experiments, the one on the magnetic, and the other on the electric deflections. Both the unknown quantities—to wit, the velocity and the ratio e/m —can therefore be found from the results of the experiments.

When a magnetic force is applied, the spot of phosphorescent light in the tube of Fig. 30 is drawn out into a band of appreciable length. This result is a consequence of a difference in velocity of the rays: in any one discharge, rays are found with a considerable range of velocity, and therefore these rays are deflected, according to their velocities, through a series of different angles.

The following table gives some of the results of Sir J. J. Thomson's experiments, and shows the mean values of the velocity, v , in centimetres per second, and of the ratio m/e for cathode rays,

m being expressed in grams, and e in electro-magnetic units of electricity.

<i>Gas.</i>	<i>v.</i>	<i>m/e.</i>
Air	2.8×10^9	1.2×10^{-7}
Hydrogen	2.5×10^9	1.5×10^{-7}
Carbonic acid	2.2×10^9	1.5×10^{-7}

Thus, within the limits of experimental error, the values of m/e are independent of the nature of the residual gas left in the vacuum tube. Moreover, in these experiments, and in a further series due to H. A. Wilson, the results were shown to be the same whatever metal was used to form the cathode. In all circumstances the mean velocity is very high, being about one-twelfth that of light, and the mean value of m/e is 1.3×10^{-7} , which makes the reciprocal ratio e/m about 7.7×10^6 .

Since the date of Thomson's original investigation, these measurements have often been repeated. More recent results, especially those of Millikan, give values for m/e of 5.64×10^{-8} and for e/m of 1.77×10^7 .

Now in liquid electrolytes, the passage of one electro-magnetic unit of electricity evolves 10^{-4} gram of hydrogen. Thus, in this case, the ratio m/e is about 10^{-4} , or about eighteen hundred times more than 5.64×10^{-8} , its value for the negative particle in a cathode ray.

But, as we have already seen (p. 134), by an application of C. T. R. Wilson's beautiful experiments on the electric formation of clouds, Thomson has proved that the individual charge on all the gaseous ions examined is the same as the charge on the ions in liquid electrolysis, and this result has been confirmed by other methods. Although

the cathode ray particles themselves could not be investigated in this way, there seems no reason to suppose that they are exceptions to a rule otherwise universal. If, then, e is the same both for gases and for liquids, m must be different; the cathode ray particle must have a mass which is only the one eighteen-hundredth part of that of the hydrogen atom.

Similar values have been obtained for the mass of the negative particles when produced in other ways. In one case, that of the ions due to the incidence at a low pressure of ultra-violet light on metals, both e and e/m have been measured for the same particles. A zinc plate is illuminated with ultra-violet light, and placed opposite to and parallel with a second metallic plate connected with an electrometer, the gas surrounding the apparatus being exhausted to a very low pressure. An electric force is established between the two plates, and the negative ions, produced at the zinc plate, are by this force urged towards the second plate. If no other agency were at work, all the negative ions would reach the second plate, and transfer their charges to the electrometer. Now let us imagine that a magnetic force is applied at right angles to the electric force and parallel to the planes of the plates. The magnetic force will deflect the negative particles from their original straight course, and their path becomes a cycloid. They travel out from the zinc plate, curve round, and approach it again. If the second plate is placed near enough to the first to intercept this curved orbit, all the ions will still reach the plate connected with the electrometer, and the rate at which it gains negative electricity will not be

affected by the presence of the magnetic field. If, however, the electrometer plate be moved away from the zinc plate till it lies beyond the path of the ions, it will receive none of them, and the establishment of the magnetic force should stop completely the supply of negative electricity to the electrometer. If X be the electric force and H the magnetic force, theory shows that no ions should cross the space between the plates if the distance between them exceeds $2Xm/eH^2$, while below that distance the addition of the magnetic force H should produce no effect on the rate of gain of negative charge by the electrometer.

The experiments which Thomson carried out by this method showed that no such sudden change could be produced. As the distance was diminished, or the magnetic field increased, at first the effect of putting on or taking off the magnetic force was small. Then a stage was reached at which a considerable effect was produced; while finally, in a third stage, the magnetic force cut off almost all the ions from the electrometer plate. This somewhat gradual change is explained if we suppose that the negative ions are not all formed at the surface of the zinc plate, but that, as the primary ions there produced move forward under the action of the electric force, they produce new ions by their collisions with the molecules of the gas. The ions are thus formed, not exclusively at the surface of the plate, but throughout a thin layer of gas near the plate. This secondary production of ions by primary ions moving with high velocities occurs in many other cases, and has been studied systematically by Townsend. It

explains the large currents which can be carried by the electric arc or spark discharge.

These considerations indicate that, in the experiments we are now describing, the limit of the second stage, in which some but not all of the negative ions are stopped by the magnetic field, gives the distance at which those ions coming from the surface of the zinc plate just fail to get across the space between the plates. The expression given above then leads directly to a value for e/m , the ratio of the ionic charge to the ionic mass. Thomson found as the result 7.3×10^6 , a number which agreed well with that which he deduced for cathode rays, namely, 7.7×10^6 .

With the negative ions produced by the incidence of ultra-violet light on a zinc plate, it is easy to repeat C. T. R. Wilson's experiments on the formation of clouds round ions as nuclei, and thus to determine the value of e , the electric charge associated with the same ions for which e/m has already been obtained. The result shows that, as always, the charge is the same as the charge on an ion in liquid electrolytes; and therefore for the ions due to ultra-violet light, as for the cathode ray particles, the mass must be much less than that of the hydrogen atom. The result has been confirmed by Lenard, who used a somewhat different type of apparatus.

In all these investigations the existence of particles much smaller than the smallest of the hitherto indissoluble chemical atoms is clearly indicated. Since the beginning of the nineteenth century the chemical atom has been the ultimate unit in which our conception of matter has been expressed. The sixty, seventy, or eighty different

elements, progressively known to the chemist, seemed to be essentially different in kind, though certain likenesses between them, and periodic relations between their properties and masses, vaguely pointed to a common origin. Now, after a hundred years, the atom yields place to Thomson's corpuscle as the ultimate known particle of matter; while the phenomena of radio-activity, as we shall see hereafter, have shaken the belief in the immutability of the elements, and are leading to a new faith in their transmutation.

Speculation, it is true, from the days of Democritus to those of Sir William Crookes, has been busy with imaginings anent ultimate particles, which should be common to all types of matter, and should compose the different elements by differences in their number or arrangement. But Professor Thomson has not followed the facile and barren paths of speculation. He has first found the particles, and has weighed and timed them before theorising on their origin and destiny.

We are now in a position to estimate the importance of the experiments which have shown that the mass of the corpuscle is independent both of the nature of the gas in which it is found, and also of the material of the electrode used in producing it. Not only must we conceive atoms to contain these more minute particles, but it is necessary to suppose that in all atoms, whatever be their nature, these particles are similar. The dream of an ultimate particle, common to all kinds of matter, has thus at length come true.

The relation between the corpuscles and the electric charges associated with them must next be considered. These isolated particles have never

been observed with positive charges ; positive ions are found to have masses equal to those of some chemical atoms. The facts may provisionally be explained by the hypothesis that the corpuscle constitutes the isolated negative unit of electricity.

Now the existence of electric units as a basis of matter had been suggested already by Lorentz and Larmor. The light and radiant heat emitted by incandescent substances are electro-magnetic waves, and must therefore arise from the vibration of electric charges. The periods of vibration are too quick to be due to the motion of atoms as wholes, and we must therefore look within the atom for the source of radiation. Hence it again follows that atoms must be complex structures with more minute internal parts containing electric charges. Those parts themselves have been pictured as electric units and given the name of electrons—a word invented by Stoney. They may be identified with Thomson's corpuscles, and these are indeed now generally called electrons.

The ordinary phenomena of electrification may be described in these new terms.

An atom of ordinary matter, with one electron beyond its proper number, is an atom negatively electrified ; an atom with the electron detached from it is an atom positively electrified. These charged atoms act as ions, negative and positive respectively, in accordance with the usual convention about signs.

A moving electrified body acts like an electric current, and therefore must be associated with electro-magnetic energy and electro-magnetic momentum in the surrounding dielectric medium. To change the velocity, therefore, requires the ex-

penditure of electro-magnetic energy, and thus the electrified body possesses electric inertia in addition to its ordinary dynamical inertia. As long as the velocity is small, this electric inertia is constant, but an electrified body moving rapidly can be shown mathematically to behave as though its inertia, that is, its mass, were increased; and, as the velocity of light is approached, this apparent electric mass grows very rapidly. Now some experiments by Kaufmann, in which the masses of the negative corpuscles emitted by radium were investigated, are of intense interest in this connection. The radium electrons move much more rapidly than those found in cathode rays, though in other respects electrons from the two sources appear to be identical. With radium the velocities are so great that they approach closely that of light. A speed of 2.85×10^{10} centimetres a second has been observed, that of light itself being 3.0×10^{10} . At these enormous velocities, Kaufmann found that the value of e/m , determined from the magnetic and electric deflections, was considerably diminished, a value of about one-third the normal being obtained. Assuming that the charge be constant, this means a threefold increase in m , the effective mass of the corpuscles.

From the theory of electrons it is possible to calculate what the increase of apparent mass should be, on the assumption that the whole of the mass of the corpuscle is an electrical manifestation, and, as we shall see in a future chapter, the results of these and later experiments agree with the calculated numbers. Such results are of fundamental importance, both physically and philosophically. It seems that the whole of the

observed mass of the electron may be regarded as an effect due to the electro-magnetic inertia of its electric charge. Representing the atoms of ordinary matter as made up of negative electrons scattered in space round some central positive nucleus, it becomes possible to explain their mass by the electro-magnetic properties of an electric charge. To explain other phenomena, it is supposed that the electrified corpuscles—the electrons—are in rapid orbital or oscillatory motion within the atom: that, for example, the electrons whirl round the nucleus in their orbits as the planets swing round the sun, and thus we get a first picture of the atom which has been filled in in much detail by later research.

Mass or inertia is the most permanent and characteristic property of matter, and having explained mass as due to electricity in motion, the physicist may well ask the metaphysical question: has matter any objective reality; may not its very essence be but a form of disembodied energy? And here the philosophical speculation of 1904 is in accord with the mathematical principle of relativity of to-day. On that principle, matter and energy are of the same nature, and both intimately bound up with the properties of that combined space-time which is more real than either time or space independently.

An attempt to obtain a more vivid picture of the electro-magnetic field was made by J. J. Thomson by means of the conception of tubes of force, a conception which we owe to the instinctive insight of Faraday. A small electrified body, carrying, let us suppose, a negative charge, is well known to attract other bodies in the neighbour-

hood when those bodies are positively electrified, and to repel them if their charges be negative. Rejecting the idea of action at a distance, Faraday regarded these electric forces as transmitted by stresses and strains in the dielectric or insulating medium, and represented the state of that medium by a series of lines, drawn everywhere so as to lie in the direction of the force on a positively electrified particle.

The distribution of these electric lines of force can be investigated theoretically, the laws of force being known, but it is not easy to illustrate them experimentally. On the other hand, the corresponding magnetic lines can be rendered visible and mapped out by a familiar experiment, which, indeed, first suggested to Faraday his conception of lines or tubes of force. If the poles of a horse-shoe magnet be placed beneath a sheet of cardboard, over which iron filings are sprinkled, a picture of the magnetic lines of force is formed by the filings (Fig. 31). Under the influence of the magnetic field, each filing becomes a little magnet, and attracts others, forming chains of filings which lie everywhere in the direction of the magnetic force. Where the force is strong, the filings cluster thickly; where the force is weak, few filings are to be seen. Thus a complete representation of the lines of magnetic force is obtained.

The laws of force are similar for electric charges and for magnetic poles, and the lines of force will possess the same form. Thus the filings in Fig. 31 represent also the direction and distribution of the electric lines or tubes of force in the neighbourhood of two electric charges of

opposite signs. Here we have two charges ; but, for an isolated charged body, the lines of electric force must evidently be radial.

Now Thomson explained electro-magnetic momentum as an effect of the Faraday tubes of force in pulling after them as they move some of the surrounding medium. A solid body moving through water drags some of the liquid with it, and, in this way, its effective mass is increased.

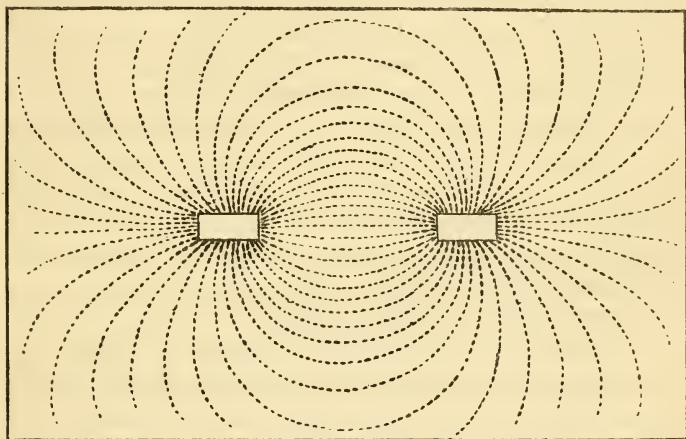


FIG. 31.

A vortex filament, too, carries with it some of the fluid of which the vortex is composed. So with the Faraday tubes if we look on them as physical realities. Maxwell showed that the same medium would explain both light and electric waves, and we may perhaps, as an illustration, think of tubes of force as vortex filaments in the luminiferous æther. We may then suppose that they move some of the surrounding æther with them. If the æther possess mass, it will endow the moving

tubes with effective momentum. In this way, Thomson regarded electric momentum as similar in kind to ordinary dynamical momentum. Should the inertia of material objects be electrical in its nature, then, on this view, the mass and kinetic energy of ordinary bodies is to be regarded as the mass and kinetic energy of the æther bound to the Faraday tubes which emanate from the constituent electrons. If such a scheme be accepted, the problem of the material universe is referred completely to the problem of the nature and properties of the luminiferous æther. A great simplification in our conception of the world is thus effected, but again, as always, an ultimate explanation eludes us. Moreover, some of the consequences of the theory of relativity, which we shall trace in Chapters VIII. and IX., show that caution and restraint are needed in dealing with the luminiferous æther. We probably know less about it than our fathers did.

Instead of stating matter in terms of electricity, it is simpler, and perhaps less ambitious, to express electricity in terms of matter, as Thomson did at first, and say that electrified atoms contain one or more corpuscles in excess or defect of their normal number. Nevertheless, the electron theory of matter, formerly supported on mathematical grounds, has been strengthened greatly by these developments of experimental science. Moreover, from the point of view of radio-activity, which we shall consider in the next chapter, that theory is of supreme importance, for it gave the first indication that an atom was a complex and possibly unstable body. Now the occasional instability of a complex chemical atom, and its disintegration

into simpler bodies, as we shall presently see, is the universally accepted explanation of the phenomena of radio-activity.

Having now dealt with the phenomena of cathode rays and the theoretical results which have followed their discovery, we must turn to the corresponding positive rays, which are emitted from the anode of an exhausted tube through which an electric discharge is passed. If holes be bored in a cathode placed opposite an anode, positive rays will be found to have passed through the holes into the space behind the cathode. They may, if necessary, be sent through a window of thin aluminium foil, and thus examined outside the discharge tube.

The magnetic and electric deflections of these anode rays are much less marked than the deflections of cathode rays, and stronger fields must be used to examine them. The results show that they are positively electrified particles, with masses corresponding to those of known chemical atoms, instead of the sub-atomic electrons of cathode rays.

It was again Sir J. J. Thomson who first made an extensive investigation of these positive rays. He passed them through both an electric and a magnetic field, so that they fell on a photographic plate in such a way that all projected particles having the same value of m/e formed a single line.

In hydrogen, for instance, the chief line is found in a position which indicates a value for m/e of 10^{-4} , the same as for the hydrogen ion in liquid electrolytes. Another line showing a doubled value for m/e indicates a hydrogen molecule carrying a single charge. In oxygen, atoms appeared carry-

ing two unit charges. In neon (atomic weight 20.2) two lines were found very near together, suggesting atomic weights of 20 and 22.

This last indication was carried further by F. W. Aston, who improved the apparatus, so that it gave a photographic "mass spectrum," and obtained most interesting and important results. The double nature of ordinary neon was confirmed. It consists of a mixture of two types of atom, identical in chemical properties, but of different atomic weight. Such bodies were named isotopes by Soddy who discovered instances in another way. Aston, extending the work on mass spectra, proved that many elements as known to the chemist consist of mixed isotopes. Thus chlorine has an atomic weight of 35.46, and, with similar cases, was always a stumbling block in the road of those who sought to reduce the elements to different combinations of hydrogen atoms as units of atomic structure. Aston showed at once that its mass spectrum gave two lines, corresponding to atomic weights of 35 and 37. The riddle of chlorine was solved: it consists of two isotopes, each atomic weight being a whole number. Similar results were obtained with many other elements.

Among the various agencies enumerated at the beginning of this chapter for the production of gaseous ions, special interest attaches to the action of incandescent metals and carbon. Elster and Geitel, Richardson, H. A. Wilson, and others have shown that, as a platinum wire is heated gradually, it begins to emit positive ions at a temperature corresponding to a low red heat. The investigation of the influence of a magnetic force shows

that these ions vary in size, some probably being molecules of the gas, and others molecules of the metal or even dust disintegrated from its surface. As the platinum is still further heated, negative ions also come off, ultimately in large excess. In vacuo the negative leak from platinum and carbon filaments is very large—from carbon it may even amount to as much as an ampère of current from each square centimetre of surface. The negative ions are then of sub-atomic dimensions, and are identical with the electrons otherwise obtained. H. A. Wilson has shown that, at the lower temperatures at which the negative leak occurs, it is very largely due to the effect of hydrogen absorbed in the platinum, and liberated under the action of the heat. At the highest temperatures, however, the electrons due to the wire itself seem to be much more numerous than those depending on the presence of hydrogen, and to the metal itself we must then look for their source.

The emission of electrons at high temperatures is not confined to solids. Thomson finds that sodium vapour also gives off a large supply, and the effect seems to be common to all kinds of matter at a white heat. Carbon is particularly efficacious, perhaps because it can be raised to a higher temperature than can most metals. It is easy to demonstrate the existence of a measurable current from one limb of the carbon filament of an ordinary incandescent electric lamp to an insulated plate placed between the limbs.

Owing to the emission of electrons by an incandescent wire or carbon filament along which a current flows, the effective current-carrying area of the wire is increased. In vacuo a considerable

fraction of the current might pass through the space surrounding the wire, which must become filled with electrons. Although in gases at ordinary pressures the emission of electrons is less copious, still, ionization will occur to an appreciable extent just round the wire, and a part, though perhaps a small part, of the current will pass along outside the substance of the wire.

The phenomena we are now considering have a practical application in the art of wireless telegraphy and telephony (see Chapter VIII.). But they also have an important bearing on cosmical processes. The photosphere of the sun contains large quantities of glowing carbon, and this carbon will emit electrons until the resultant positive charge left on the sun exerts an electro-static force great enough to prevent further emission. In this way a condition of equilibrium would be reached. Any local elevation of temperature would then cause a stream of electrons to leave the sun and pass into the surrounding space. When electrons pass through a gas with high velocity, they make it luminous, and Arrhenius and others have explained many of the periodic peculiarities of the Aurora Borealis by the supposition that electrons from the sun, due either to incandescence or to some other cause, stream through the upper regions of the earth's atmosphere.

The phenomena of electrolytic conduction through liquids, and of non-electrolytic conduction through metallic substances, must now be interpreted in terms of this electronic theory. The chemical decomposition of electrolytic solutions,

which we have described in Chapter V., indicates that an electric transfer through such liquids involves a movement of the chemical constituents of the substance decomposed. In fact, as we have seen, that movement has been experimentally demonstrated, and the passage of the ions rendered visible. We must suppose, then, that the electron forming the effective negative essence of the anion, is, in liquid electrolytes, attached to an atom of matter. This atom may possibly be associated with other atoms or molecules forming a complex ion, but the point is that the isolated electron cannot slip from one atom to another, and thus carry an electric current through the liquid; the electron cannot move without a corresponding movement of matter—of matter, that is, in its atomic or molecular sense.

Here again the motion of the positive ion involves the simultaneous passage of a particle of matter of at least atomic dimensions. The positive ion consists of an atom of the electrolyte with one of its electrons missing. In this way, a unit of negative electricity is removed from it, that is, it is left with a positive charge.

In metals an electric current flows without chemical change in the substance of the conductor, so that, in this case, we must imagine the electrons to be freely mobile. They pass from atom to atom, and thus carry the current when an electromotive force acts. In the presence or absence of such a force, they may be regarded as existing within the metal in a state resembling in many ways the state of a gas in a closed vessel. Estimates have been made of the number of electrons present in a given volume;

of the velocity with which they move under an electric force ; and of their mean free path within the metal, that is, of the average distance an electron moves between its collisions with other electrons. As we have seen, when the metal is heated, the electrons begin to leave it, and stream away into the surrounding space. At any constant temperature equilibrium is set up between the electrons leaving the metal owing to the effect of temperature, and those drawn back again by the residual positive charge on the metal. We may look on the system as analogous to a liquid in equilibrium with its own vapour.

In the last chapter we saw that it was necessary clearly to distinguish the electric current and the heating effect of the current from the flow of the energy by which the current was maintained. The energy passes through the surrounding medium, through the luminiferous æther. The current is merely the line along which the energy of the æther can be dissipated as heat. Faraday and Maxwell showed that the medium invoked to explain the phenomena of light was also competent to explain electric and magnetic manifestations. An electric force is a state of strain in the æther, and the immediate function of an electric machine or voltaic battery is to set up such a state of strain. If the poles of the battery are insulated from each other, the state of strain is maintained, the poles are attracted towards each other with a small force, but nothing else happens. Faraday, as we have seen, represented this state of strain by drawing lines of force, or tubes of force, which map out the electric field, and everywhere follow the direction of the electric force. The tubes of

electric force end on the surfaces of conductors, and the opposite ends of each tube, where they touch the conductors, constitute unit electric charges of opposite sign. The state of strain in the field is such that we must imagine the tubes of force as tending to shorten in length and to push each other apart; and, when the poles of a battery are disconnected, the tubes of force will be in equilibrium under these forces. The distribution of the electric tubes will then be very similar to that of the magnetic lines, made visible by the filings shown in Fig. 31 on p. 153.

A conducting wire must be regarded as a channel along which the free ends of a line or tube of force can move, and, when the poles of the battery are connected by means of a wire, the tubes of force in the surrounding air run their opposite ends on to the wire, pull those ends towards each other, and shut up. Other tubes are then pushed into the wire by their mutual transverse pressure, and are obliterated in turn. The tubes of force in the dielectric field are thus inclined to disappear, and the state of æthereal strain in that field tends to be relieved. Simultaneously, however, the battery endeavours to reassert the original distribution of tubes, and once more to set up the strain. In this way new tubes are constantly forming between the terminals of the battery, and are as constantly pushed into the connecting wire, where they vanish. When the connection is metallic, it is only the negative ends of the tubes, attached to the electrons, that move, the positive ends remain at rest. If, on the other hand, part of the circuit is composed of an electrolyte, in that

part the positive ends of the tubes are also mobile. Now it is this continual process of establishment of æthereal strain by a battery, and the compensating process of its obliteration along a conductor that, according to the views of Faraday and Maxwell, now accepted as one aspect of the truth, constitute an electric current.

The ionic theory of electrolysis gave a clear idea of the mechanism by which the slipping of the ends of the tubes of force occurred in conducting liquids, and the electronic hypothesis gives us an equally vivid insight into the nature of the process within metallic circuits. The tubes, anchored by their ends to an ion in electrolytes or to an electron in metals, drag their anchors. It is the slip of the anchors that constitutes the current, and the heat developed by the passage of the current is to be explained by the frictional resistance to the drag of the anchor, or to some other means of dissipating energy, such as internal radiation, not yet fully understood.

Faraday had no skill in mathematical analysis, and his insight into physical principles is one of the best examples of scientific instinct found in history. As was well said by Von Helmholtz in the Faraday Lecture for the year 1881, "Now that the mathematical interpretation of Faraday's conceptions regarding the nature of electric and magnetic forces has been given by Clerk Maxwell, we see how great a degree of exactness and precision was really hidden behind the words, which to Faraday's contemporaries appeared either vague or obscure; and it is in the highest degree astonishing to see what a large number of general theorems, the mathematical deduction

of which requires the highest powers of mathematical analysis, he formed by a kind of intuition, with the security of instinct, without the help of a single mathematical formula. I have no intention of blaming his contemporaries, for I confess that many times I have myself sat hopelessly looking upon some paragraph of Faraday's descriptions of lines of force, or of the galvanic current being an axis of power."

Such a confession from a man of the commanding ability of Von Helmholtz shows how far the instinctive genius of Faraday had carried him in advance of his age. "We must also in his case acquiesce in the fact that the greatest benefactors of mankind usually do not obtain a full reward during their lifetime, and that new ideas need the more time for gaining general assent the more really original they are, and the more power they have to change the broad path of human knowledge."

CHAPTER VII

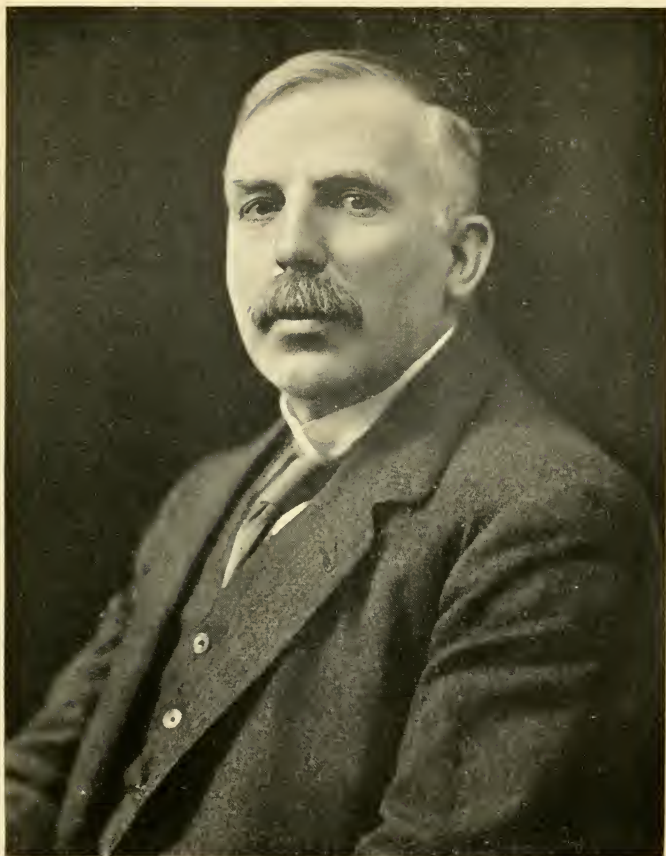
RADIO-ACTIVITY

To watch the abysm-birth of elements.

—KEATS, *Endymion*.

SCIENTIFIC investigation, which usually proceeds unmarked by most of those not directly engaged in it, is from time to time forced on the attention of the public by some discovery of immediate and striking advantage to mankind, or by the attainment of some theoretical result, which, from its novelty and interest, fires the imagination of every thinking man.

To those who follow closely the course of research, these brilliant advances in knowledge rarely come suddenly. The slow and patient work of many observers through long years often leads up to and suggests the particular step from which follows, almost of necessity, the practical application or the far-reaching theory. The mathematical genius of Clerk Maxwell, the experimental skill of Hertz, laid the foundations on which, years afterwards, was reared the superstructure of wireless telegraphy. The observations of Crookes, Lenard, J. J. Thomson, and many others, on electric discharges through rarified gases, had given to the physicist an extended insight into the nature of these phenomena, before Röntgen's almost accidental discovery—that photographically active rays thus



E. Rutherford

obtained could traverse certain substances opaque to light—revealed the bones in his hand to the man in the street.

General attention was first directed to the subject of radio-activity when in 1903 M. Curie demonstrated that the stream of energy proceeding constantly from the newly-discovered element radium could be detected by a measurable rise of temperature in a small quantity of the substance protected from loss of heat. From then onwards, an unbroken series of successful experimental researches and brilliant theoretical generalisations have together vastly extended our knowledge of nature and revolutionised the outlook of physical science.

In this case also the essential phenomena have been under investigation longer than is generally known; and their detection naturally arose from a knowledge of the properties of Röntgen rays. These rays produce fluorescent effects on suitable screens; and it was natural to examine phosphorescent and fluorescent substances, to determine if they were the source of similar radiation. For some time no definite results were obtained; but, in the year 1896, M. Henri Becquerel discovered that compounds of the metal uranium, whether phosphorescent or not, affected a photographic plate through an opaque covering of black paper, and rendered the air in their neighbourhood a conductor of electricity.

Such were the first observations on the property of radio-activity; but the rapid development of the subject which has followed could only have taken place with the aid of our previous knowledge of the electrical properties of gases.

Although the superficial similarity between Becquerel rays and Röntgen rays has proved for the most part misleading, the relations between the two branches of the subject are so intimate that it is impossible to study satisfactorily the phenomena of radio-activity without a knowledge of the results previously and simultaneously reached by the investigation of electric discharge through gases.

After Becquerel's discovery of the photographic and electric activity of uranium, it was found that, like Röntgen rays, the rays from uranium produced electric conductivity in air and other gases through which they passed. Compounds of thorium, too, were found to possess similar properties. In the year 1900, M. and Mme. Curie made a systematic search for these effects in a great number of chemical elements and compounds, and in many natural minerals. They found that several minerals containing uranium were more active than that metal itself. Pitch-blende, for instance, a substance consisting chiefly of an oxide of uranium, but containing also traces of many other metals, was especially active. When obtained from Cornwall its activity was about equal to that of the same weight of uranium, but samples from the Austrian mines were found to be three or four times as effective. The presence of some more active constituent was thus suggested. To examine this point, the various components of pitch-blende were separated chemically from each other and their radio-activities determined. In this way three different substances, radium, polonium, and actinium, all

previously unknown, were quickly isolated by different observers. Of these three the most famous is the now well-known radium, discovered by M. and Mme. Curie, working with M. Bémont.

Radium is obtained from pitch-blende in company with the metal barium; and the two seemed at first to be connected chemically so intimately that the new substance was for a time called "active barium." However, a slight difference in the solubilities of some of their salts allows them to be separated gradually by a process of repeated fractionisation, the radium chloride and bromide crystallising out more readily than the corresponding compounds of barium.

These processes of chemical separation were remarkable for their use of the new property of radio-activity as a sole guide in the operations. After each reaction the activities of both the product and the residue were determined. It was thus settled whether the reaction just tried was effective, and in which of the substances separated by the reaction the property of radio-activity had been concentrated.

The quantity of radium present in pitch-blende is extremely small, many tons of the mineral yielding, after long and tedious work, only a small fraction of a gram of an impure salt of radium. Its extraction is consequently a matter of great labour and high cost. Radium salts of fair purity have now become articles of commerce, though the supply is insufficient to meet the demand; and radium is at present worth many thousand times its weight in gold.

An interesting point in these investigations is the extreme sensitiveness of the property of radio-

activity as a test for the presence of those substances which possess it. A delicate electroscope will show easily a leak of electricity with a substance having an activity of about the one-hundredth part of that possessed by uranium. The activity of pure radium has been estimated as about two million times that of uranium; and such radium is a definite, well-marked chemical element, like other elements, forming salts and other chemical compounds, and giving strong bright lines when heated and examined with a spectroscope. Spectrum analysis has hitherto been the most delicate means at our disposal for detecting the presence of the chemical elements; but in the preparation of radium from pitch-blende its spectrum only began to appear when, in the prolonged process of fractionisation, the product had reached an activity of about fifty times that of uranium.

It appears from these figures that the electroscopic method of detecting radio-active matter is several thousand times more sensitive than the most refined methods of spectrum analysis, and in other cases a still greater sensitiveness seems to have been reached. History has again repeated itself. When the spectroscope was first placed in the hands of chemists, it revealed the existence of several elements which occurred in quantities too small to be detected by any other means then known. In a similar way additional elements have now been detected and isolated by the help of the newer and more powerful method of research.

In the year 1899 Professor Rutherford of Montreal, now Sir Ernest Rutherford, Cavendish Professor at Cambridge, discovered that the radiation from uranium consists of two distinct parts.

One part was found to be unable to pass through more than about four layers of thin aluminium foil, while the other part would pass through about one hundred layers before its intensity was reduced by one half. The first named, or α rays, produce the most marked electric effects, while the more penetrating, or β rays, are those which affect a photographic plate through opaque screens. At a later date was detected a third type of still more penetrating radiation, known as γ rays, which can traverse plates of lead a centimetre thick, and still produce photographs and discharge electroscopes. In proportion to its general activity, radium evolves all three types of radiation much more freely than uranium, and is best employed for their investigation.

The moderately penetrating or β rays can be deflected easily by a magnet; and Becquerel, who deflected them by an electric field as well, conclusively proved that they were projected particles, charged with electricity. M. and Mme. Curie had shown previously by direct experiment the existence of a negative charge associated with these rays. Owing to their ionizing action, it is impossible to demonstrate that a body surrounded by air gains a charge when exposed to the rays. Such a charge would leak away as fast as it was acquired. But, by working in a very good vacuum, or by surrounding the body with a solid dielectric such as paraffin, the acquisition of a negative charge can be demonstrated by means of an electrometer. Further investigation showed that the β rays behave in all respects like cathode rays, although they possess greater velocities than any cathode rays hitherto examined, velocities which

have different values ranging from 60 to 95 per cent. of the velocity of light. The β rays, then, are negative corpuscles, or negative electrons.

Magnetic and electric fields which are strong enough to deflect considerably the β rays, produce no effect on the easily absorbed α rays. R. J. Strutt, now Lord Rayleigh, suggested in the year 1900, that the α rays were positively charged particles, of mass greater than that of the negative β particles, but it was not till some time afterwards that their magnetic and electric deviations were demonstrated experimentally, and shown to be in the direction opposite to that observed with β rays. The mass of the carriers in the α rays, as calculated from the deviations, is the same as that of helium atoms—more than four thousand times that of the negative electrons—and the positive charge associated with the particles is found to be double that on a univalent ion. The velocity is about one-tenth of that of light.

The very penetrating or γ rays have never been deflected, and from this fact it has been supposed that they are different in kind to the other types, and, like the X-rays discovered by Röntgen, consist of electro-magnetic waves similar in nature to light but of shorter wave-length. On the analogy of the cathode rays, we should expect that such pulses would be started as a secondary effect of the β rays. In 1903, Strutt published experiments which show that, as with the α and β rays, and also with the cathode rays, different gases absorb the γ rays in direct proportion to the density. The absorption phenomena exhibited by ordinary Röntgen rays are of an entirely different kind. But very "hard" Röntgen rays

—that is, the extremely short electro-magnetic waves produced by the cathode rays of very high vacua—show absorption phenomena similar to those of the γ rays of radium. Forasmuch as the β rays travel with velocities higher than those of any ordinary cathode rays, we should naturally expect the resulting waves to have shorter wave-lengths than ordinary Röntgen rays. The nature of γ rays was finally placed beyond dispute when the same experiments on crystals were carried out with them as had been so successful with X-rays. The γ rays also showed diffraction phenomena, and gave several spectral lines of wave-length about 10^{-8} centimetres. It seems certain then that the γ rays are identical in nature and origin with very “hard” Röntgen rays.

All the three types of radiation, when they pass through air or any other gas, render the gas a conductor of electricity, so that the charge of an electroscope or of an electrometer leaks away. The charged particles of atomic mass which constitute the α rays, the negative corpuscles or electrons which form the β rays, and the γ rays, short electric waves, are all able to convert some of the molecules of a gas into electrified ions. The α and β projectiles probably effect this change by the energy of their collisions with the molecules of gas, and it is possible to estimate the number of ions produced by each shot. It has been reckoned that this number is sufficient to give air a measurable conductivity when one positive particle per second is emitted by the radio-active substance. Even if one atom of radium emits only one such particle, this estimate means that the electroscope is able to detect

effects which depend on one atom coming into action each second. We may well be astonished at the delicacy of this means of research.

Again, all three kinds of rays produce phosphorescent and photographic effects, though the penetrating power of the β and γ rays makes the phenomena due to them more remarkable.

Radium salts are self-luminous, owing either to the direct emission of light by their agitated atoms, or to some phosphorescent effect of the internal bombardment produced by their radio-activity. The spectrum of this spontaneous luminosity was photographed by Sir William and Lady Huggins, and shown to correspond with the spectrum obtained by passing electric sparks through nitrogen. Sir William Crookes and Sir James Dewar found that this spectrum vanished when the radium compound was placed in a high vacuum. Probably, therefore, it is due to the effect of the activity of the radium on atmospheric nitrogen surrounding the radium salt or occluded within it.

A screen of the phosphorescent substance, zinc sulphide, when placed in the neighbourhood of a radium compound, glows brightly, and Crookes has used this property in a most striking and beautiful experiment. A tiny fragment of a radium salt is fixed at the distance of a fraction of a millimetre in front of a plate covered with zinc sulphide. On looking through a lens or a low-power microscope in a dark room, brilliant scintillations are seen, and the effect of the atomic projectiles of the α radiation as they strike the target is thus made visible to the human eye. In 1908 Rutherford used this effect to count the

number of α particles in a narrow pencil of the rays, and recalculated from his results several radio-active constants.

In the year 1900 Rutherford made another striking discovery. The radiation from thorium was known to be very capricious, being affected especially by slight currents of air passing over the surface of the active material. Rutherford traced this effect to the emission of a substance which behaved like a heavy gas having temporary radio-active properties. This emanation, as it was named, is to be distinguished clearly from the radiations previously described, which travel in straight lines with velocities approaching that of light. The emanation diffuses slowly through the atmosphere, as would the vapour of a volatile liquid. It acts as an independent source of straight line radiations, but suffers a decay of activity with time.

Similar emanations are given off by radium and actinium, but not by polonium or uranium. The emanations seem to be very inert chemically, in this resembling gases of the argon group. They pass unchanged through acids or hot tubes, but are condensed at the temperature of liquid air, evaporating again as the tube is warmed. By taking advantage of this property, many pretty lecture-room experiments may be performed. For example, a quantity of radium emanation is condensed in a tube surrounded with liquid air. The tube is connected with others, and, if the liquid air be removed, the emanation can be traced as it diffuses, by the fluorescence it excites on the glass, or on small pieces of paper covered with zinc sulphide, which are placed here and there

within the tubes. By measuring the rates of diffusion of the emanations into other gases, their densities have been determined approximately and found to be of the order of two hundred times that of hydrogen.

When the emanations come into contact with solid bodies, they cause these bodies themselves to become temporarily radio-active. This radio-activity, which, in some cases, is found to be acquired more readily by negatively electrified surfaces, has been traced to radio-active deposits clinging to the surfaces. Whatever the effective substance may be, it may be treated chemically, and can be dissolved in some acids and regained as a radio-active residue on evaporation.

All the three types of radiation considered above, and known as α , β , and γ rays, have one remarkable property which, at first sight, is not shared by the emanations just described. The radio-activity of any element, with regard to the emission of these rays, is independent of the compound in which that element is contained. Thus, for a mass containing the same amount of the element radium, the activity of radium chloride is the same as that of radium bromide; while uranium, the metal, has the same activity as it has when combined chemically in uranium nitrate. Moreover, an alteration in the physical conditions, such as temperature, which always largely influence the course of ordinary physical and chemical changes, seems, throughout an extended range, to be entirely without effect on the processes involved in radio-activity. Heating to redness, or exposure to the extreme cold of liquid air or liquid hydrogen, equally leave the activities we

are considering untouched. In liquid hydrogen most chemical activities are entirely suspended, and these results, to whatever cause they may be due, are very remarkable. It seems certain that, even when we approach the absolute zero, all the activities of radium are quite independent of temperature. Such extraordinary results as these point to a deep-seated difference in kind between the radio-active processes and all chemical and physical operations hitherto investigated. We shall presently examine this point more closely.

Unlike the "straight line" radiations of the types α , β , and γ , the emanations discovered by Sir Ernest Rutherford are emitted much more freely from some compounds of the radio-active element than from others, while the rate of emission is largely dependent on physical conditions, such as the temperature of the system. By a striking series of experiments, however, Rutherford traced these differences to variations in the ease with which, after formation, the emanation escapes from the generating substance.

Let us consider these results in more detail. It is found, for example, that while the emanation is given off very slowly from dry and solid radium chloride, it is emitted freely from the same salt in solution. This allows the problem to be submitted to the test of quantitative experiment. The rate of decay of the radium emanation is known; its activity falls to half value in 3.7 days. Thus, the activity of the emanation stored in a solid radium salt reaches a limit, when its rate of decay becomes equal to the constant rate at which the emanation is produced by the radium. On the hypotheses that the emanation is formed at the same rate in

the solid as in the solution, that it escapes from the solution as fast as it is formed, and that it does not appreciably escape from the solid at all, it is clearly possible to calculate the amount of emanation that should be stored in the solid, as compared with the amount produced and emitted by the solution in a given time.

The calculation shows that 463,000 times more should be stored in the solid than is emitted by the solution in one second. Now if, as supposed, the emanation is stored in the solid, this large amount will be liberated instantaneously when that solid is dissolved in water. Rutherford and Soddy measured this rush of emanation by its effect on an electroscope, and found that it was 477,000 times greater than the quantity afterwards developed by the solution in one second: a remarkable confirmation of the several hypotheses given above.

The effect of raising the temperature is similar to that of solution. When a solid radium compound is brought to a red heat, a rush of emanation takes place, which makes the initial emanating power some hundred thousand times greater than that of the cold solid. This high rate of emission, however, does not last; it, also, is due to the rapid escape of stored material.

By experiments such as these, the emanating power of radio-active elements has been brought into line with their other radio-active properties, and has been shown to depend only on the mass of the element present, whatever be the state of combination in which that element exists, and whatever be the physical conditions under which the process occurs.

Soon after appreciable quantities of radium were available for investigation, Giesel drew attention to the fact that a radium compound gradually increases in activity after formation, and only reaches a constant state after a month's interval. Similar phenomena were observed by Curie and Dewar for the heat effect. These results are readily explained if we consider the properties of the emanation as elucidated by the experimental evidence that has now accumulated.

When a salt of radium is dissolved in water, and the solution boiled, the emanation previously stored in the salt is evolved and removed. The residual activity of the salt is then found to be much diminished. This activity must include that due to the radium itself, and also that of the active deposit, which has been developed by the emanation, but is not removed with it. The effect of the active deposit decays rapidly; after a few hours it will nearly have vanished, and we then get the true activity of the pure radium salt alone, uncomplicated by that of the emanation, or by that of the active deposit which is produced by the emanation.

This residual, non-separable activity is found to consist entirely of α rays, and, measured electrically, is about 25 per cent. of the normal activity of a radium compound after a month's existence; a normal activity which comprises the combined effects of radium, of the radium emanation, and of the active deposit.

Rutherford and Soddy studied these relations in detail. They dissolved a radium compound, removed the emanation, and waited till the activity of the deposit had subsided. The solution was

then evaporated, and the recovery of the activity of the solid crystals of salt was traced by measuring at intervals the ionizing power. The results are shown in Fig. 32, where, neglecting the residual activity, the recovery curve of the activity of the salt is compared with the curve of decay of activity of the separated emanation. It will be seen that the two curves are complementary to each other; the activity of the emanation falls

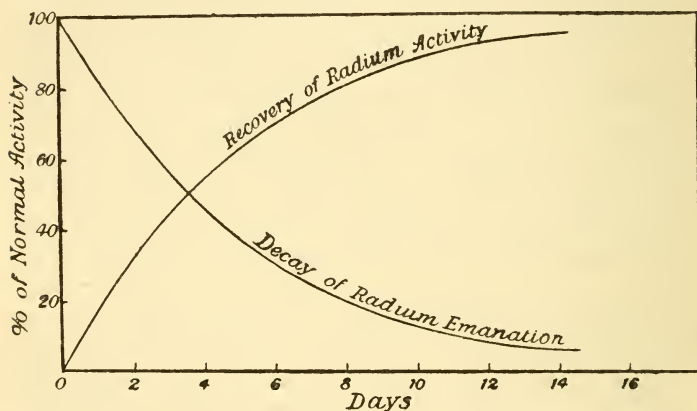


FIG. 32.

to half its initial value in a little less than four days, and the purified radium salt recovers half its final activity in the same time. If the activity of the emanation at any instant be added to that of the recovering radium, the result is equal to the normal activity of the radium when fully recovered. Thus the total activity of the residual radium and its separated emanation, considered together, remains constant throughout, though resolved into constituent portions. This result again illustrates the characteristic feature of radio-

active processes: the impossibility of changing the amount of activity by any ordinary chemical or physical operations.

Since the phenomena of radio-activity have been well known, and the various types of radiation and emanation which proceed from radio-active materials clearly distinguished, traces of the property have been found to be disseminated very widely. Mr C. T. R. Wilson, for example, detected radio-activity in newly-fallen rain and snow; when evaporated they leave a residue which discharges an electroscope. Again, Sir J. J. Thomson found that when air is bubbled through various samples of water from deep wells, or when the water is boiled and the dissolved air driven off and collected, there is present in the air a radio-active gas, which behaves as though it were the emanation from some active substance of which slight traces are contained in the water. The air loses its active properties, while the water regains a small part, and after some days will again yield a supply of active gas. The rate of recovery and decay seem to be about the same as for the radium emanation, and this suggests that the active material is radium in minute quantity.

Again, M'Lennan, Rutherford and Cooke, and Strutt found that the rate of leak in a closed vessel depends on the nature of the walls of the vessel. But Strutt detected some variation in the rate of leak with different samples of the same material, and Cooke diminished the rate of leak in a brass electroscope by carefully cleaning the walls. Probably this result is to be explained

by the presence of slight traces of some active emanation in the atmosphere, and the consequent active deposit on solid materials, which active deposit is removed by cleaning. Nevertheless, it seems that a few elements such as potassium, not classed as radio-active, show the effect to an extent just measurable.

The air of the atmosphere itself, when tested with a sensitive electroscope, is found to possess a slight conductivity. It seems likely that this effect is due to traces of some radio-active substance, whence issue the radiations which ionize the air. The rate of leak of electricity through air has been shown by Elster and Geitel to be greater in a cave or cellar than in the open; while air drawn from a clay soil contained a radio-active emanation. From such experiments we know that traces of some radio-active substance are present in many places in the earth; on the other hand, we know that some active bodies emit radiations of an extremely penetrating nature. It thus seems reasonable to believe that the slight conductivity which appears to exist at all times in the atmosphere is due to the production of gaseous ions by the action of stray radiations proceeding from some radio-active material, near or far.

It was hoped at first that radium might play a useful part in the curative treatment of certain diseases. Röntgen rays have occasionally been employed as a means of checking the spread of cancer, and the radiations from radium also appeared to be effective, besides being applied far more easily locally, and for considerable

periods. But there are grave difficulties in the use of radium, for we are as yet very ignorant of its entire physiological action ; its after-effects on those who have handled any large quantity for some time are far from reassuring.

The medicinal springs of Bath and Buxton contain radio-active emanations, while radium itself has been detected in the solid deposits at Bath. It is possible that the curative effects of these waters is caused by their radio-activity, and if so, the uselessness of drinking the water, when kept and removed to a distance, may be due, more to the decay of the activity of the emanations, than to the provident imagination of the local authorities.

In seeking an explanation of these physiological effects, some experiments, due to Mr W. B. Hardy, must be noticed. As we have seen in Chapter V., solutions of salts and acids, which are conductors of electricity, possess the power of coagulating clear solutions of colloidal or jelly-like substances such as albumen or sulphide of arsenic, and this action is readily explained by referring the coagulative action to the electric charges on the ions.

The influence of charged ions on colloidal solutions being thus made clear, Hardy tried the effect of exposing a very sensitive solution of globulin, a substance contained in the living tissue of animals, to the charged particles emitted from radium, which produce ions so readily when passing through a gas. The penetrating β rays were without action, but the easily absorbed α rays, which enter a film of the liquid when it is placed near a radium salt with no screen interposed,

immediately coagulated the globulin. On the other hand, the β and γ rays were found to induce certain chemical reactions, liberating iodine from iodoform in presence of oxygen. This change is also produced by ordinary light and by Röntgen rays, but not by the α radiation. These results, physical and chemical, may explain some of the curious physiological effects of radio-active substances.

It seems unlikely that radio-activity will ever be cheap enough for us to use its energy to develop mechanical power, but it is just possible that the phosphorescence of sensitive screens in the neighbourhood of a radio-active body may some day be employed as an effective source of light. In this way luminous effects would be obtained directly from a store of energy self-contained and practically inexhaustible, whereas, in all our present arrangements, light is derived from a hot body, and large quantities of energy are necessarily wasted in maintaining the incandescence.

In order to gain some insight into the cause of radio-activity, we must now examine another series of phenomena of fundamental importance, which were discovered in the case of uranium by Crookes and by Becquerel, and in the case of thorium by Rutherford and Soddy. By definite processes of chemical fractionisation, somewhat like those by which radium was isolated from pitch-blende, products can be obtained in minute quantities from uranium and thorium many times more active than those substances themselves. The uranium and thorium from which those products have been separated lose much of their activity; the radiation

they then emit seems to be an inseparable property of the elements themselves, and is of the α type only. To the separated products the names of uranium- X and thorium- X have been given. They may be analogous to emanations as far as the series of radio-active changes is concerned, being, however, solid instead of gaseous at ordinary temperatures.

The important point is this : if these X products be kept for some weeks or months, they will be found to have lost their radio-active properties, while the original samples of uranium or thorium will have become as active as they were before the separation, and will again emit all three types of radiation. The rates at which the processes of loss and gain of activity occur have been studied carefully by Rutherford and Soddy, and shown to correspond accurately with each other. This correspondence is clearly shown by the curves in Fig. 33, which give the decay of activity of the separated uranium- X , and the recovery of the residual uranium. Again we see that the total amount of activity remains constant, and is not affected by the processes of chemical action.

These experiments lead to a definite view as to the source of the radiations. Whenever radio-activity exists, the active material is always slowly changing into some other substance, which has distinct chemical properties, and can be separated by chemical means from the original material. Thus, in the case of thorium compounds, the radio-active body producing most of the effects usually observed is not really thorium, but a definite substance we may call thorium- X , which is being formed at a constant rate from the bulk of the thorium, and, after its formation, gradually loses

its activity. The radio-activity of the pure thorium seems to be a consequence of its change into thorium-*X* and to accompany that change. The activity of the thorium-*X*, in a similar way, accompanies, and is a consequence of, its continual change into other bodies, in this case, the thorium emanation. The constant activity of a thorium compound, as ordinarily found, is thus due to a

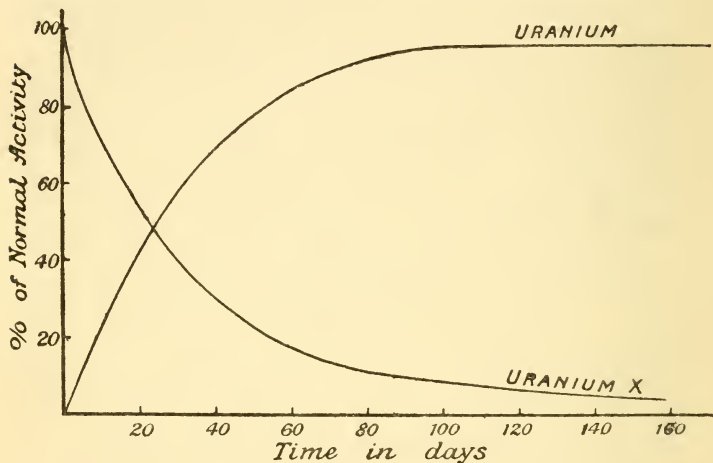


FIG. 33.

balance in the rate of production of the active thorium-*X* and the rate of its loss of radio-activity.

What view are we to take of the changes in the thorium or uranium which result in the formation of the *X* products, and what further changes must we suppose to go on when the *X* products give rise to emanations or other bodies? Are these changes of the nature of ordinary chemical action, in which atomic or molecular combinations, or rearrangements of the atoms in a molecule, are

involved, or must we look deeper for their causes?

Three essential pieces of evidence should be considered in this connection. The rate at which radio-active power is gained or lost depends only on, and is always proportional to, the total amount of active material at any instant remaining effective; it does not depend on the concentration of that material. For instance, if the activity of a quantity of thorium-*X*, or of radium emanation, be examined, it will be found to decrease during each unit of time by the same fraction of the value it had at the beginning of that interval. If, in the first four days, the activity falls to half its initial value, during the second four days it will fall to half that half-value, or to one quarter of the initial value; during each successive four days the remaining activity is halved, the process being represented by a curve of the type of those in Figs. 32, 33. The rate of decay does not depend on the volume which the material occupies. This mode of change in a geometrical progression, depending only on the total amount of effective material present at the instant, is well known in chemical processes. In such processes it always indicates that the reaction is an alteration going on in the individual molecules, which may either be dissociating into simpler molecules, or be suffering a rearrangement of their constituent atoms. Each molecule undergoes this change alone, and does not react with other molecules. If, on the other hand, a change is going on, in which combination or rearrangement between two reacting systems is involved, whether the systems consist of atoms

or molecules, another law holds ; and the rate of change is found to increase when the material is concentrated into a smaller space, so that the two systems are more closely within reach of each other. In the phenomena we are considering, then, the change involves one system only, whatever that system may be.

In examining the further question thus raised, we are confronted at once with the remarkable fact that the radio-activity of a series of compounds of any radio-active element is simply proportional to the amount of the element which they contain. The activity of the element is not affected by its state of combination, or by very great changes in the physical conditions, such as temperature, which play a large part in determining ordinary physical or chemical equilibrium. As we have seen, this remarkable result applies not only to the emission of the "rays," but also to the formation of the emanations which proceed from some of the radio-active elements ; the differences in emanating power have been traced to differences in the rate at which the emanations can escape from the various compounds under various conditions. The law of decay of activity shows that one reacting system only is involved ; these further phenomena show that the system does not alter with the changing conditions which are found to affect all known molecular processes, or with the state of combination which affects the physical and chemical properties that control the behaviour of the elements in all other respects. Moreover, as we shall see later, it is possible to calculate the energy liberated by a given amount of radio-active change. This energy is several

million times greater than that involved in the most energetic chemical action known.

The conclusion is thus forced on us that, in radio-active processes, we are dealing with changes in the atoms themselves, and are watching the phenomena which accompany a true transmutation of the elements. The continuity of the problems which present themselves to the human intellect is once more strikingly demonstrated, for surely the imagination must be deficient which does not see in these transformations of matter a partial fulfilment of the dreams of the mediæval alchemist.

The strength of any hypothesis lies in its power of co-ordinating observed facts, and of forecasting intelligently the discoveries of the future. If, then, we accept this new revelation, and in its light reconsider the phenomena we have already discussed, we shall be able to marshal our facts in orderly array, while the few privileged pioneers alone can tell how much assistance they received from it in their brilliant achievements.

Let us then, in terms of this new theory, restate the results which we have already described. All radio-active elements have very high atomic weights, the atom of radium, for instance, being 226 times as heavy as that of hydrogen. Radio-active atoms are therefore very complex structures, and, on the theory we are considering, are capable of breaking down into simpler and lighter systems. The elements thorium and uranium contain some few atoms which, at any moment, are disintegrating. As we have seen, the activity of the pure separated thorium or uranium consists of α rays only. Thus, the essential process of the radio-

activity of these bodies consists in the emission of α rays, the disintegration of each atom resulting in the projection of one or more α particles with a velocity about one-twelfth that of light, while the residues break down into new and simpler atoms, which are themselves in a state of instability, and are known to us as thorium- X and uranium- X .

The further transformation of these bodies is very rapid, their activity disappearing in a time to be measured in days. In radium we possess an analogous substance, also an intermediate product in a state of instability, the life of which is enormously longer. The primary substance, standing to radium as thorium stands to thorium- X , was discovered by Boltwood and named ionium. It is itself derived from uranium through uranium- X and two other intermediate products.

In compounds of radium and thorium, we get the emanations as a step in the process of atomic dissociation. These bodies also are unstable, that is, radio-active. They emit new α rays, and produce the radio-active deposit which generally appears on the walls of the containing vessel. This again breaks down, with the usual accompaniment of α radiation. The decay of the active deposit on a rod, exposed for a very short time to the radium emanation, is shown in Fig. 34. The curve is a complicated one, and may profitably be compared with the simple curves giving the rate of decay of the activity of uranium- X , the curve of Fig. 33 on page 184, and with the curve of decay of the radium emanation, Fig. 32 on page 178. Rutherford has shown, however, that the complex curve of the decay of the excited activity of radium can be made up by the con-

junction of several constituent curves, of the usual typical form shown by uranium-*X*. At least three successive changes in the radio-active matter are indicated: the actual curve is the resultant of these three processes, which are going on

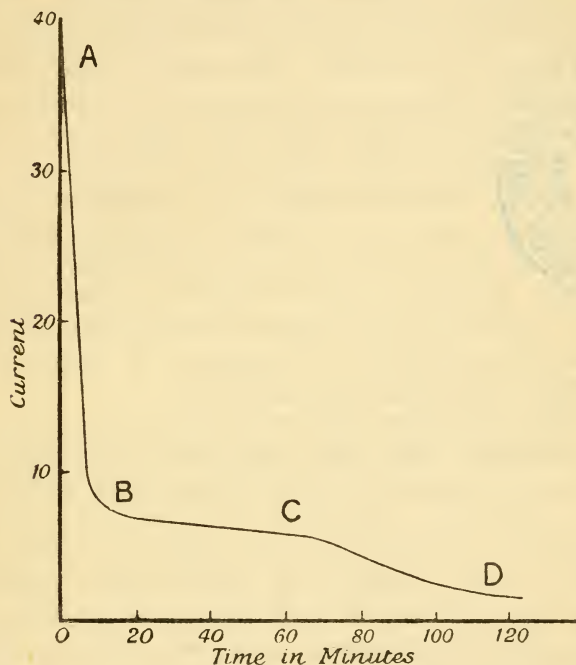


FIG. 34.

simultaneously. If the measurements be confined to the β and γ rays, it is found that the activity rises from zero to a maximum before it begins to decay. Radium, radium emanation and its first product emit α rays only, the second product gives β and γ rays, and the third product all three types of radiation.

Evidence of further changes is also forthcoming. Surfaces exposed to the emanation of radium retain a small part of their residual activity for several years without appreciable diminution. By taking advantage of differences in volatility and other properties, Rutherford has traced three more stages in the transmutation of the radium products. The first is half accomplished in about sixteen years, and involves β and γ rays; the second takes six days, and is also accompanied by the emission of β and γ rays; while the third, marked by α radiation, needs 136 days to sink to half its initial activity. Rutherford calls the deposited radio-active matter radium A, B, etc., and writes these eight generations of the radium pedigree as: Radium, radium emanation, radium A, radium B, radium C, radium D, radium E, radium F.

Radium F has been shown by Rutherford to be identical with the substance separated by Madame Curie from pitch-blende and called by her polonium. Could it be prepared pure, it should be several hundred times as active as radium, but, as half of it would vanish in about 143 days, the labour and expense needed for its separation would afford but a short-lived specimen for the investigator.

A somewhat similar series of changes has been made out in the case of thorium. Another radio-active constituent too has been separated from pitch-blende and named actinium by Debierne. It is derived indirectly from uranium and forms an X product, an emanation, and several solid deposits distinguished as actinium A, B, C, and D.

The quantities of matter involved in any radio-

active change are excessively minute, and no other method at present known enables us to detect the final inactive products as they are formed. It is, however, not improbable that, by the slow accumulation of material which must of necessity go on when a radio-active body is kept for a long time, the inactive products will be obtained eventually in amounts sufficient to be distinguished by the spectroscope or even by ordinary chemical analysis. In this connection attention was soon called to the fact that in all radio-active minerals lead is found and considerable quantities of helium gas are occluded.

Sir William Ramsay and Mr Soddy, by spectroscopic methods, detected helium in the gases evolved from a sample of radium, originally prepared from pitch-blende and kept as a solid for some months. The spectrum of helium was invisible when the emanation was first collected and examined, but soon appeared and gradually increased in intensity with the lapse of time.

Similar results were then obtained by Dewar and Curie, who, moreover, traced the disappearance of a minute volume of the emanation. This has been explained by the idea that the resulting helium, being projected in the atomic state with great velocity, penetrated the glass walls of the vessel and thus occupied no volume. The decrease in the volume of a minute quantity of emanation was also observed by Ramsay and Soddy.

This question, however, has been settled finally by the researches of Rutherford and his fellow-workers. Measurements of the magnetic and electric deflection of the α rays had indicated that the α particles ejected by any single active sub-

stance had approximately the same velocity, but that velocity depended on the substance used. Radium emanation, for instance, emits α particles with a velocity of 1.62×10^9 , while those from radium C move with a speed of 1.92×10^9 centimetres per second.

On the other hand, for all α particles, whatever their source, the ratio e/m of the charge to the mass is constant, and equal to about 4820 electromagnetic units. The value of e/m for the hydrogen ion in liquid electrolytes is 9649 in the same units. If, therefore, the α particle carries the same unit electric charge as the hydrogen ion, its mass must be twice as great; but if it carries a double charge its mass will be four times that of the hydrogen atom and equal to that of helium.

Clearly, then, the determination of the charge carried by the α particle was a problem of fundamental importance, and this problem was attacked by Rutherford and Geiger.

We have already described the scintillations produced on a screen of zinc sulphide by the impact of the α rays from a minute speck of a radium compound. Rutherford and Geiger proved that each particle causes a visible scintillation, and then counted the particles emitted by a measured amount of a radium product. They also used another method. A quantity of gas at a low pressure exposed to an electric field of force just not strong enough to give a spark, is in a very sensitive state. An α particle shot through it produces a large number of ions by collision with its molecules, and each of these ions is set in motion by the electric force, producing other ions in its turn. Each α particle in this way,

directly or indirectly, gives rise to some 40,000 ions or more, enough to give the gas a measurable conductivity. If, therefore, an electrometer be inserted in the circuit, the flight of each α particle is shown by a transient deflection—by a visible movement of a spot of light reflected from the needle of the instrument on to a scale. It will be noted that, in these two ways, Rutherford and Geiger detected the effect of an individual atom—a crowning verification for Dalton's atomic theory.

The number of α particles emitted per second by the product radium C in radio-active equilibrium with 1 gram of radium was thus estimated at 3.4×10^{10} . The same number must be emitted by the gram of radium itself, and by each of its three α ray products—radium emanation, radium A, and radium C. Consequently 1 gram of radium and its products in equilibrium emit 13.6×10^{10} α particles per second.

Having counted the number, the next thing was to estimate the total charge of the particles. The α rays are intercepted by an insulated plate, and the gain in electric charge by the plate is measured by an electrometer. The charge carried by each α particle was found to be 9.3×10^{-10} electrostatic units. This result was confirmed by Regener, who obtained the figure 9.6×10^{-10} from radium F.

Now Millikan's value for the single unit charge carried by electrons on univalent ions is 4.77×10^{-10} electrostatic units. Thus it is clear that the α particle carries two positive electric units, and has a mass four times that of a hydrogen atom—that it is, in fact, a helium atom with two unit charges, shot forth with high velocity.

To verify this result, Rutherford and Royds repeated and improved the earlier spectroscopic experiments. A quantity of radium emanation was compressed into a tiny thin walled capillary glass tube. The α particles, shot through the thin walls, were collected in another glass tube which surrounded the inner one. After a few days the complete spectrum of helium was seen by sparking the gas from this outer tube. The α particle has an atomic mass of 4 and a charge $+2e$. When its velocity is destroyed by passing through matter, it absorbs two negative electrons, and becomes an ordinary neutral helium atom. Helium is one final product of radio-active atomic disintegration.

In the course of this investigation, we have seen that the number of α particles emitted per second by a gram of radium was estimated as 3.4×10^{10} . That result enabled Rutherford incidentally to calculate the rate of decay of the radio-activity of radium, and therefore the life of radium itself. The activity would fall to half-value in 1730 years, and we may therefore conclude that a mass of radium would disintegrate at a speed which would destroy half of it in that time.

Each exploding radium atom emits an α particle—a helium atom of atomic mass 4 with two positive electric charges. Hence the atomic weight of the residue is reduced by 4 and radium, with an atomic weight of 226, passes into radium emanation with an atomic weight of 222. So radium A must have an atomic weight of 218, and radium B of 214. But radium B passes into radium C by ejecting β and γ rays only, hence it suffers

no appreciable change in mass and the atomic weight of radium D is also 214.

Now let us consider the changes in electrical charge. When radium loses an α particle, it loses also two units of positive charge. We shall see later that there is reason to believe that what is called the atomic number of radium, a number which measures the essential electric charge on the atomic nucleus, is 88. Hence the nuclear charge or atomic number of the emanation is 86, of radium A is 84, and of radium B, 82. Since in each case the whole atom is neutral, it has to discard also two of the electrons from the outer orbits. The whole change involves a complete rearrangement, and consequently a new atom.

When radium B explodes, it emits only β and γ rays, and in losing a β particle it loses a negative electron with a single unit charge. The high speed of the β particle shows that it comes from the nucleus, and thus the residual nucleus, though it has practically the same mass as its parent, has increased its charge by one unit and become a new atom with quite different properties. And so the whole series of radio-active changes down to radium F or polonium has been traced.

The question of the ultimate fate of the radio-active matter remains. What becomes of radium F when it in turn disintegrates? No product has been detected by radio-activity, and, if the substance formed is not active, we can only investigate it by examining minerals, where the slow accumulation of ages has gone on. Now Boltwood pointed out that in minerals from the same geological formations, and therefore presumably of about the same age, the contents of lead are proportional to

the contents of uranium and radium. Thus lead was indicated as the last traceable stage in the

Pedigree of the Radium Family.

	Atomic Number.	Atomic Weight.	Time of Half-decay.	Radio- activity.
Uranium . . .	92	238	5×10^9 years	α
↓				
Uranium X ₁ . . .	90	234	23.5 days	β, γ
↓				
Uranium X ₂ . . .	91	234	1.17 minutes	β, γ
↓				
Uranium II . . .	92	234	2×10^6 years	α
↓				
↓ Ionium . . . ↓ Radium . . . ↓ Radium Emanation . . ↓ Radium A . . . ↓ Radium B . . . ↓ Radium C . . . ↓ ? ↓ Uranium Y .	? 90	? 230	25.5 hours	β
↓				
Ionium . . .	90	230	2×10^5 years	α
↓				
Radium . . .	88	226	1730 "	α
↓				
Radium Emanation . .	86	222	3.85 days	α
↓				
Radium A . . .	84	218	3.05 minutes	α
↓				
Radium B . . .	82	214	26.8 "	β, γ
↓				
Radium C . . .	83	214	19.5 "	α, β, γ
↓				
↓ Radium C₁ . . . ↓ Radium D . . . ↓ Radium E . . . ↓ Radium F (Polonium) . ↓ Lead . . . ↓α Radium C₂ .	81	210	1.38 "	β, γ
↓				
Radium C ₁ . . .	84	214	? 10^{-6} seconds	α
↓				
Radium D . . .	82	210	16.5 years	β, γ
↓				
Radium E . . .	83	210	4.85 days	β, γ
↓				
Radium F (Polonium) .	84	210	136 "	α
↓				
Lead . . .	...	206	...	...

series of disintegrations we have followed. In recent years, Soddy has proved that the lead

from radio-active minerals has an atomic weight appreciably different from that of other lead. To such elements with different atomic weights but identical chemical properties, he gave the name of isotopes. We have seen in Chapter VI. how Aston has discovered many other isotopes by a quite different method.

It is now time to put together the complete pedigree of the radium family as investigated by our radio-active genealogists. No place is found for thorium and its derivatives. They seem to form a separate and independent radio-active family. Another radio-active family of some ten generations is that of actinium. It is probable that this is a collateral branch of the radium family derived from uranium Y.

Such is the theory of radio-activity indicated by the remarkable series of investigations that have followed Becquerel's original discovery. We are led to refer the energy liberated to transformations in the chemical atoms, and to recognise clearly, what has long been suspected, that the store of energy in the atoms themselves enormously transcends the energy involved in ordinary physical or chemical changes, in which the atoms suffer no alteration. This internal atomic energy, then, must be looked on as the source of the heat detected experimentally by Curie in the neighbourhood of a radium compound. Its immediate cause may be, partly at least, the internal bombardment of the α particles, which, shot off by the radium and the emanation stored in it, are for the most part absorbed by the substance itself. Rutherford has traced the increase of the heat effect in radium

bromide newly precipitated from solution, and has shown that it grows *pari passu* with the radio-activity as measured electrically—a method which, as we have seen, depends chiefly on the α radiation.

The greater part of the radiation coming from a solid radium compound is emitted by the stored emanation and its products, the active deposits. The emanation can be extracted only in such minute quantities that, except in most exceptional conditions, its radio-activity alone reveals to us its existence. As we have seen, the emanation is of the nature of a dense gas, half of any quantity of which would be transformed into other substances in about four days. Owing to this process of change, only a limited amount of emanation can be obtained from a given quantity of radium, and the bubble which can be evolved from the small supply of radium possessed by any experimenter is too minute to be visible, except by the most refined and sensitive methods of investigation. Could a cubic inch of the radium emanation be obtained, the radiation from it would be so powerful that the vessel used to contain the gas would, in all probability, be fused instantly.

By the methods we have already described, it is possible to determine the mass and the velocity of the projected particles, and therefore to calculate their kinetic energy. From the principles of the molecular theory, we know that the number of atoms in a gram of a solid material is about 10^{20} . Eight successive α ray stages in the disintegration of radium have been recognised; and, since each of these involves the emission of one particle, the total energy of radiation which 1

gram of radium could furnish if entirely disintegrated seems to be enough to raise the temperature of about 1.5×10^{10} grams, or about 15,000 tons of water, through one degree centigrade. We may say that, in mechanical units, the energy available for radiation in one ounce of radium is sufficient to raise a weight of something like five thousand tons one mile high.

It will now be clear that, on the theory which has been put forward, we are, while investigating a radio-active body, in reality watching the process of the transmutation of matter. Radio-active substances, themselves unstable, may have been formed by the disintegration of parent atoms, which are unknown to us, and, indeed, may now be non-existent on our globe. Radio-activity denoting an unstable state, it is probable that the total amount of it in the world is constantly diminishing, as the atoms of the active elements pass gradually into inactive forms. Perhaps in former ages nearly all matter was intensely radio-active; and mankind has discovered these phenomena only in the last cosmical moments of a few thousand or million years before they cease for ever to manifest their existence in the striking manner which has made radium so remarkable.

When we trace in this way the creation and evolution of new elements, it is impossible to resist wondering whether the process of change, so far observed to an appreciable extent only in a few radio-active bodies, may not in reality be a general property of matter, though in other cases possessed in such an infinitesimal degree that it almost transcends the delicate means of detection

that are now at our disposal. As we have seen, experimental evidence is not altogether wanting in favour of such a supposition. We must, at any rate, cease to regard matter as essentially eternal and unalterable; the possibility of its undergoing a continual though slow process of disintegration is clearly before us.

A striking property of radio-active change is our inability to produce it, or even to modify its course, by any of the usual means within the resources of modern physical science. The highest temperature we can employ on the intense cold of liquid air, the most complete vacuum attainable on a pressure of a thousand atmospheres, are equally useless. The observation that the activity of radium is independent of the concentration of the material shows that the disintegration of one part of this substance is not accelerated by the radiation from another part. Even under the fierce and continuous bombardment of the atomic projectiles hurled forth by radium, and the sharp musketry of its corpuscular β rays, the residual atoms of radium are unaffected. They remain unchanged by the action of any internal agency, till, in the fullness of time, their own internal processes result in instability, and, from the shattered fragments of each radium atom, as, in its turn, it breaks asunder, new elements emerge.

But in 1922 Rutherford announced the result of some experiments in which the atoms of certain elements had been broken up by the bombardment of α particles. Heavy atoms such as those of radium seem to resist all such attempts, but with some types of lighter atoms success was attained.

That bombardment by α rays is the most promising mode of attack, is clear from figures. These particles are projected with speeds some twenty thousand times greater than that of a rifle bullet, while mass for mass their kinetic energy is four hundred million times that of a bullet.

If α particles, that is helium nuclei of atomic mass 4, be fired into hydrogen gas, occasional collisions give rise to fast moving hydrogen nuclei, that is charged hydrogen atoms, which will penetrate some 30 centimetres of air and produce scintillations on a zinc sulphide screen. If oxygen or carbon dioxide be substituted for hydrogen, a few of these scintillations, due to traces of hydrogen impurities, are still seen. But, if dry air, or still better nitrogen, be used, many more scintillations appear, and still persist if the screen be moved far beyond the 30 centimetres, or be covered with a screen equivalent to this thickness of air, that is, if the screen is out of shot for the nuclei produced by collision between α rays and hydrogen molecules.

Their magnetic deflections indicated that the projectiles were still singly charged hydrogen nuclei, but moving with much higher speeds than those obtained by collision in the free hydrogen molecules, thus confirming the evidence of their great power of penetration. It seems to follow that these fast moving hydrogen atoms can only be obtained by an explosion of nitrogen atoms, induced by the impact of the α particles.

The effect of α particles on solids was then investigated by firing them at very thin films with oxygen gas beyond. Of all the elements examined, the following alone give the same

result as nitrogen (14): boron (11), fluorine (19), sodium (23), aluminium (27), and phosphorus (31). All these elements, and possibly a few others, give hydrogen scintillations beyond the range of ordinary hydrogen, and are therefore thought to be broken up by the bombardment.

This interpretation is confirmed by the evidence of the atomic weights. The atomic weights of the elements named are given by the general formulæ $4n + 2$ or $4n + 3$, where n is a whole number. Other elements such as oxygen (16) or carbon (12), which have atomic weights represented by $4n$, are not active. Now when we come to deal with the modern theory of the atom, we shall see that these latter elements may be supposed made up of n helium nuclei each of weight 4, while the active elements have two or three units in addition, which may well be hydrogen nuclei each weighing one unit. Hence all the evidence is in favour of the view that the nuclei of the atoms of the elements boron, nitrogen, fluorine, sodium, aluminium, and phosphorus are built up of helium and hydrogen, and that the nucleus is shattered by α rays, with the ejection of hydrogen particles.

We shall consider the problem of the structure of the atom in greater detail in the next chapter; here we are concerned only with the broad result that Sir Ernest Rutherford has not only taught us that radio-activity is due to the spontaneous explosion of atoms, but has now shown us how to produce disintegration in elements usually inactive, by using the concentrated energy of an α ray projectile.

Thus we approach even nearer to the hope

of the alchemist. But it is easier to destroy than to build up, and it does not follow that, because we can knock to pieces one atom in a million, we shall ever be able to put together a more complex atom from simpler ones.

Moreover, the number of atoms affected is almost infinitesimally small. About two α particles in a million dislodge hydrogen nuclei. If all the α particles from a gram of radium were steadily fired into aluminium, only about the one-thousandth part of a cubic millimetre of hydrogen would be produced in a year. The modern philosopher's stone falls far short of medieval requirements.

By investigating radio-active changes, we can trace the transmutation of the elements; we can watch the disintegration of matter; we can even knock to pieces a few atoms of certain elements; but we are far from bringing these processes fully under our control. It would be rash to predict that our impotence will last for ever. It is conceivable, too, that some means may one day be found for inducing radio-active change in elements which are not normally subject to it—means more effective than bombardment by the comparatively few α particles which have yet been used. Sir Ernest Rutherford once playfully suggested to the writer the disquieting idea that, could a proper detonator be discovered, an explosive wave of atomic disintegration might be started through all matter which would transmute the whole mass of the globe, and leave but a wrack of helium behind. Such a speculation is, of course, only a nightmare dream of the scientific imagination, but it serves to show the illimitable avenues of thought opened up by the study of radio-activity.

CHAPTER VIII

MATTER, SPACE, AND TIME

Oh, dear ! what can the matter be ?

—*Old Song.*

OUR primary conception of matter as continuous in time and space fails to correspond with phenomena which are perceived as soon as inquiry passes beyond the most elementary stages. The expansion of a quantity of gas without assignable limit can hardly be represented mentally if the gas is thought of as a homogeneous substance filling completely the space in which it exists. We cannot imagine that the same amount of substance fills equally at different times volumes different from each other. The immediate difficulty disappears if we suppose the gas to consist of a number of discrete particles, which can be pressed nearer together or allowed to move farther apart.

The phenomena of diffusion, too, clearly indicate that liquids and gases must consist of particles in motion relatively to each other, capable of penetrating the interspaces between the similar particles of contiguous bodies. A vessel filled with hydrogen and a vessel filled with oxygen, when opened into each other, soon contain an equal mixture of the two gases, while two solutions in contact gradually become of uniform concentration throughout. Nor are such

processes confined to fluids. Sir William Roberts-Austen has shown that gold, if placed in intimate contact with lead, will diffuse at ordinary temperatures to such an extent that, after the lapse of some years, it can be detected in the lead by chemical analysis at distances of a millimetre or more from the surface of contact. Chemical analysis is by no means one of the most sensitive methods of research, and to be discovered in this way the gold must have migrated to a considerable extent.

Again, our usual conceptions of the nature of heat rest on the view that it is a form of energy—the energy of agitation of particles too small to be recognised or controlled individually by ordinary mechanical means. No hypothesis previously proposed fulfils the needs of a satisfactory explanation.

While the most obvious phenomena thus point consistently to the conception of the grained structure of matter, the more recondite branches of physical science indicate the same conclusion by evidence which, in its cumulative effect, is irresistible. The phenomena of liquid electrolysis, no less than those of gaseous discharge and radioactivity, have been successfully co-ordinated and explained by ionic hypotheses which are an extreme form of molecular theory. Indeed, we have now several methods by which the individual atom may be made manifest to our imperfect senses. Crookes and Rutherford have shown that the molecular bombardment of each individual α particle from radium may be rendered visible by the scintillation produced on a fluorescent screen of zinc sulphide.

Rutherford and Geiger, as explained on p. 192, have detected by the throw of the needle of an electrometer the flight of each α particle shot through a gas in a strong electric field. C. T. R. Wilson has shown how to make the tracks of individual α particles visible by the lines of cloud formed upon them. And, as we know, α particles are positively electrified helium atoms.

Turning to chemistry, we are again impelled to molecular conceptions by the familiar evidence on which rests Dalton's atomic theory. It is true that at one time an alternative explanation, based on the principles of energetics alone, was put forward. As we have seen in Chapter IV., mixtures possessing a maximum or minimum melting or boiling-point change their state without change in composition of either phase. The particular composition at which this mode of change occurs depends in general on the physical conditions, such as pressure. If, however, as a limiting case, variation in conditions is without effect, the system would be classed as a compound or an element—a compound if the constancy extends only over a limited range, an element if no known variation of conditions will alter the composition. This attempt to connect matter and energy was premature and has been discarded. But modern views of atomic structure and other physical problems have suggested another, and more deep-seated relation between the two fundamental concepts of matter and energy. To this point we shall return.

Truth may possess many aspects, but, since the time of Dalton, it has been safe to accept

provisionally the idea of the molecular structure of matter. The next point to consider was whether it is possible to obtain any exact knowledge of the dimensions of this structure, that is, of the number of molecules we must suppose to exist in a cubic centimetre, and of the size of the molecular individuals.

It is clear that the molecules must be at least as small as the most minute piece of matter we can prepare and recognise, and in many ways it is possible to obtain substances in a very fine state of division. Gold leaf can be beaten out till its thickness does not exceed the millionth part of an inch, while the deep blue colour of thin smoke coming from a wood fire shows that the particles therein are able to distinguish selectively the various waves making up a beam of white light, and must therefore be comparable in minuteness with the lengths of those waves.

Such results as these, while fixing an upper limit to the size of molecules, are powerless to assist in the determination of a lower limit, smaller than which the inter-molecular distances cannot be. Such inferior limits can, however, be determined, and to one of the methods by which they have been obtained—one due to Lord Kelvin—we will now turn.

A soap bubble always tends to contract and diminish its area, and therefore, in order to increase its size, it is necessary to do work against the force of contraction to an amount which may be calculated by measuring the surface tension of the film. Adding the energy required to prevent the film from cooling during its extension, we can calculate the total work absorbed per unit increase

of area. By continual extension it would be possible to expend an unlimited quantity of work, as long as no change in the nature of the film took place under the influence of the progressive expansion and consequent attenuation of the film. The point at which it is natural to expect that some change would occur is that moment when the two sides of the film have been brought so near to each other, by the process of continual thinning, that the outside faces confining the film come within range of each other's molecular forces. But, however far the film be extended, it is evident that, as long as it remains a film, less work must be used than could otherwise be expended in evaporating the film and converting its substance into steam, since by this means its molecules would be separated completely from each other's sphere of influence. The value of this latter amount of work is known from other experiments, and is measured by the latent heat of evaporation of the substance of the film, which is composed almost entirely of water. It is possible, therefore, to calculate for the film a hypothetical thickness, certainly less than the critical thickness at which it would begin to show new properties owing to the approach of the opposite faces within molecular distances. Numerical results show that this limiting thickness may be put at about 10^{-8} of a centimetre. There are thus not more than ten million molecules in a row in a length of a millimetre, and two hundred million in the space of an inch. The numbers in the corresponding volumes will be found by cubing these values; a cubic centimetre of water contains not more than 10^{24} molecules.

This, as we have indicated, is a maximum estimate; it is possible than the number is less.

As already suggested, the interdiffusion of gases also leads to a molecular conception of their structure, and from the observed values of the coefficients of diffusion, and of the allied property viscosity, it is possible, from the principles of the kinetic theory, to calculate more exactly the number of molecules in a cubic centimetre of a gas. The results of the investigation indicate about 2.5×10^{19} molecules per cubic centimetre. Since water, the liquid, is about 1200 times denser than its vapour, it follows that a cubic centimetre of water contains about 3×10^{22} molecules, a number which may profitably be compared with the maximum estimate given above. Such figures do indeed convey little to the mind; but it may be useful to remember that the thinnest line clearly visible in a good microscope—a line with a thickness approaching the hundred-thousandth of a centimetre—would need about three hundred molecules to stretch across it from side to side. Thus the molecular structure of matter is not immeasurably finer than magnitudes which, with the aid of modern instruments, our senses are enabled to apprehend.

Our mental picture of matter, then, is that of a discontinuous substance; we can, moreover, form some notion of the number of grains in a given volume, and we know some of the chemical properties of the individual grains. But what is the nature of these particles? Are they similar in kind to the matter-in-bulk they compose, or

do the properties of matter-in-bulk appear as a consequence of the collaboration of vast numbers of particles essentially different in nature from any lump of matter we can touch or see? Again, are the particles which make up different kinds of matter different from each other, or has all matter a common constituent? Are the different elements composed of identical particles of which the number and arrangement form the determining factors of the chemical atoms?

Such questions have puzzled mankind from early times, and, until theories began to be founded on facts and tested by experiment, the track of history is strewn with the speculative hypotheses of the metaphysicians and the poets. Here and there a lucky guess or shrewd suggestion chances to agree with the views which represent, temporarily it may be, the conclusions of experimental science. It is curious and interesting that, to many highly educated people, the problems connected with the constitution of matter are better known by such triumphant proofs of the sagacity, scientific insight and good luck of some Greek philosopher than from the definite theories, slowly put together by Kelvin, J. J. Thomson, Rutherford, and Bohr, on the firm basis of experimental knowledge.

The problems at issue could not even be formulated profitably till the work of Dalton and Avogadro had fixed our ideas of atoms and molecules. In the light of present knowledge, we define an atom to be the smallest particle of matter which can take part in chemical action, or enter into the chemical structure of a compound. It is the ultimate chemical unit; the particles

smaller than an atom were discovered by physical means, and are but parts of the structures which take part in ordinary chemical action. The atom is, moreover, defined as the unit of the chemical elements. An atom of a compound is a meaningless term; the atoms of water, for instance, would be, not water, but hydrogen and oxygen.

As to the outward chemical nature of atoms, physics has had till lately little to say; but molecules, on the other hand, from the first had to be regarded either in a chemical or in a physical aspect. Chemically they are the ultimate units of the compound, the smallest parts of that compound which can exist and still retain the properties of the compound. Any further subdivision would result in the liberation of the elements. Physically, on the other hand, molecules are the smallest particles of matter which act as wholes in the incessant irregular movements which the particles of matter are always undergoing. The energy of these molecular movements is the energy of heat; and, in the most striking case, that of a gas, the impact of the molecules on the walls of the containing vessel gives the physical explanation of the pressure which the gas exerts. It is evident that the physical molecule may contain one or more chemical atoms. Clear evidence shows that in well-known gases such as oxygen and hydrogen, the molecule consists of two atoms, while some gases like argon and the vapours of some metals, mercury, for example, possess monatomic molecules.

Thus the relations between atoms and molecules are ascertained, and further inquiry must

deal with the intimate structure of the atom, as the more fundamental unit.

The essence of Dalton's great conception was that the relative chemical combining weights of the different elements lead directly to a knowledge of the relative weights of the atoms of those elements. Since Dalton's time it has been recognised that the atoms, in the chemical sense of the word, of different elements must have different weights and different properties. If, then, we look for some common constituent composing the different elementary substances known to chemistry, we must look within the atom; we must cease to regard it as the ultimate unit, and examine the internal structure of the atom itself; we must abandon the etymological meaning of the word, retaining it only for its historic associations.

On arranging the elements in order of their atomic weights, Mendeleeff discovered that periodic relations become apparent between the physical and chemical properties, elements with similar properties recurring at constant intervals. This periodicity was so marked a feature that it was possible to arrange the elements in groups, in which the various properties were possessed by the individual members to a greater or less extent, according to their position in the groups. It was even possible successfully to predict the atomic weight, properties, and compounds of undiscovered elements from knowledge of the behaviour of their neighbours, which were situated round empty spaces in the periodic table.

The periodic law suggests a common origin for the elements, and indicates that, as we pass from light to heavy atoms, we are going from

simple to complex structures containing different numbers of some common sub-atom. The atomic weights of many elements are nearly simple multiples of that of hydrogen, and Prout suggested that hydrogen was the ultimate basis of other elements. More accurate chemical experiments did not eliminate the divergence of some atomic weights from whole numbers, and Prout's hypothesis for many years was discarded; but the idea of some common constituent in the different elements has a deep scientific instinct and even then some experimental evidence in its favour, and only waited for definite confirmation to be received as the natural conclusion of many promising speculations.

For the first time, in 1897, such definite experimental confirmation was given by Professor J. J. Thomson, who, in the remarkable series of researches described on pages 142 to 147, clearly showed that, in the cathode rays of a vacuum tube, we can detect corpuscles with about the one thousand eight-hundredth part of the mass of the lightest atom known, that of hydrogen. These corpuscles were shown to be identical, whatever the nature of the residual gas in the tube, and whatever the metal employed as electrode. The corpuscles are common to all kinds of matter, and the mind at once sees in them a common constituent of all the chemical atoms.

To explain the phenomena of radiation, that is the emission of electro-magnetic waves, we must suppose with Lorentz and Larmor that the parts of atoms which vibrate are electrical in nature. As explained above, we thus reach the idea of electric units on electrons as components of

matter and may identify them with Thomson's corpuscles.

Then came the discovery of radio-activity, throwing a new light on the problem of atomic constitution. Atoms appeared as complex structures, some of the heaviest of which break down spontaneously, leaving a new and somewhat lighter element as residue, and ejecting charged helium atoms in the form of α particles and electrons as β particles.

The first detailed picture of a modern atom was drawn by J. J. Thomson, who published in March 1904 a mathematical investigation of the conditions of stability of systems of revolving corpuscles, and thereby deduced in a most remarkable manner many of the properties of the different chemical atoms. He supposed any one atom to consist of a uniform sphere of positive electrification, the structure of which is not specified, and of a number of negatively charged corpuscles revolving in orbits within that positive sphere, under the influence of the attraction of the positive electricity and of their own mutual repulsions.

A similar problem was long ago attacked by Mayer by means of experiment. A number of little magnetised needles were thrust through corks, and were allowed to float on the surface of water with their axes vertical. The similar poles of all the magnets were directed upwards, and thus the resultant force between the magnets was a repulsion. High above the water was placed a powerful bar magnet, with that pole downwards of which the magnetisation was opposite in kind to that of the upward poles of the little floating magnets. This large pole attracted inwards all the little

poles pointing upward, and thus the magnets were drawn towards the centre by the attraction of the big magnet suspended above them, and at the same time were repelled from the centre by their mutual repulsions. Under the influence of these two forces they assumed positions of equilibrium.

Mayer found that as long as the number of little magnets was not more than five, they arranged themselves in a single ring, but that, on increasing the number to six, a discontinuity of arrangement was observed; the single-ring structure ceased to be stable, and the magnets placed themselves with five in a ring and one at the centre. This two-ring configuration persisted as more magnets were added, till the number rose to fourteen, with five in the middle ring and nine in the outer circle. With fifteen magnets this arrangement in its turn became unstable, and a three-ring system appeared.

Thomson overcame the difficulties of the mathematical analysis, and has shown that similar phenomena of disposition must appear in the system which, as described above, he imagines to correspond with the atom. Here also, discontinuities in arrangement will appear, and, when certain definite numbers of electrons have come together, an additional ring will be formed. Periodic likenesses in structure also arise and will give to the system in which they occur similarities of periods of vibration, and, it was thought, might explain the homologous series of lines which are found in the spectra of elements lying in the same group of Mendeleeff's periodic classification.

So far the theory had been carried when this book first appeared. But, as we shall see below,

the central force is now supposed to be connected with a minute positively electrified nucleus and not with a sphere of positive electricity as large as the atom.

Thomson thus accepted the nuclear atom, and revised his theory in its terms. He imagines that within a given distance from the nucleus its attraction for an electron changes to a repulsion. At this critical distance a single electron will rest in equilibrium. Two electrons will rest on opposite sides of the nucleus, three at the corners of an equilateral triangle, four at the corners of a regular tetrahedron, and so on up to eight. With nine electrons, eight will form an inner shell round the nucleus, and one will stay outside, further from the centre of the atom. This outer layer increases regularly in number as we pass to heavier atoms and more electrons are added, till it too contains eight electrons.

Now, while radio-activity is an affair of the nucleus, the chemical properties of the atom depend on the outer electrons. As we shall see below, the atoms of hydrogen and lithium have each one electron, and the number will rise as we pass up Mendeleeff's Periodic Table, as shown in the following list of a few of the lighter elements :—

Number of	Lithium.	Beryllium.	Boron.	Carbon.	Nitrogen.	Oxygen.	Fluorine.	Neon.	Sodium.	Magnesium.	Aluminium.	Silicon.	Phosphorus.	Sulphur.	Chlorine.	Argon.	Potassium.
Free electrons in the atom	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Electrons in the outer layer . .	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8	1

Thus the periodicity in the properties of the elements is reproduced in the number of electrons in the outer layer. It is clear that these electrons are specially concerned in chemical reaction. The valencies of the elements, that is, the number of simple atoms like hydrogen or chlorine with which these atoms will combine, rise from one to four as we pass from lithium to carbon or from sodium to silicon. Nitrogen and phosphorus can be both pentavalent and trivalent, oxygen and sulphur are divalent, fluorine and chlorine monovalent, while neon and argon do not react. Hence it seems that the valencies depend on the number of these outer electrons from 1 to 4, and decrease again as the numbers rise higher.

We may picture chemical combination between two atoms as due to the forces between their nuclei and the free electrons of their outer layers. The simplest case, the union of two hydrogen atoms to form a hydrogen molecule, may be represented by Fig. 35, in which A and B are the positive nuclei, and α and β two negative electrons. A repels B and α repels β , while A and B attract both α and β . The electrons may then be regarded as common to both atoms, and, on this theory, that arrangement is the meaning of chemical combination.

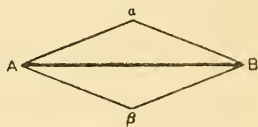


FIG. 35.

At first sight we may well say that Thomson's corpuscle—one of the latest conceptions of science—does but carry us back to the ideas and speculations of Democritus, and justify the glorification of those ideas in the poem of Lucretius, though

internal evidence seems to show that Lucretius himself did not find the explanation easy to reproduce :—

Nec me animi fallit Graiorum obscura reperta
Difficile inlustrare Latinis versibus esse.

If, however, in one aspect these modern corpuscles may resemble the hard, impenetrable atoms of the Greek philosopher and the Latin poet, such a resemblance vanishes when we identify them with the disembodied charges of electricity, mathematically studied by Larmor and Lorentz. If the corpuscle is a negative electron—a disembodied ghost—an electric charge—we enter a region of knowledge the bare existence of which was unknown to the ancients.

The hard particle of Democritus, which, as late as the age of Newton, still served as a working hypothesis, gradually failed to respond to the demands made on its constitution by both philosophers and physicists, in their search for a conceptual model of the chemical atom. Pictures of mere lumps of stuff, similar in kind to the perception of matter-in-bulk given by our senses, were no help to the theories of the metaphysician, while the complexity of structure, demanded by the facts of radiation as disclosed by the spectro-scope, showed that an atom must be capable of many and various modes of vibration.

In extreme opposition to the hard impenetrable sphere of Democritus, we have Boscovich's idealistic conception of atoms as centres of force. This theory gave too little scope for definite development to serve permanently as a useful working hypothesis, and, in face of the phenomena of

atomic radiation, it too seemed insufficient. It is worthy of note, however, that Faraday, in his day, and Lord Kelvin, in more recent years, have advocated views differing but little from those of Boscovich; while the school of chemists, who tried to banish from their ken all atomic theories, regarded energy as the only physical reality known to us, and matter as "a complex of energies which we find together in the same place."

It seemed at first that a real advance had been made when Lord Kelvin applied the theory of vortex rings, developed by Von Helmholtz and himself, to explain the properties of the atoms of matter. A smoke ring, blown in air, soon dies away, but even this evanescent thing, while it lasts, shows a definite separation from the surrounding medium, and maintains an independent existence. Air is an imperfect fluid, and movement in it is resisted by the frictional forces due to its viscosity, but, if we imagine the air to be replaced by a hypothetical perfect fluid, in which there is no viscosity, vortex rings, once formed, will persist for ever. In a fluid not quite perfect, their life will be long, though not eternal.

Here then was a striking representation of some of the most important properties of the chemical atoms. The structure of interlacing systems of vortex rings gave sufficient complexity to explain radiation, the infinite possibilities of variation in number and arrangement of the rings would account for the relations between different atoms as manifested in the periodic law, while the persistence of matter could be explained if a perfect or nearly perfect fluid were postulated as the basis of the vortex motion.

At this point we reach for the first time in our inquiry the idea of an all-pervading medium—an idea which has played such a large part in the development of physical science, that a considerable digression will be necessary. Newton explained the phenomena of light by a corpuscular theory. He supposed that streams of corpuscles were projected from luminous objects, and produced the sensation of sight by impinging on the nerves of the eye. Ultimately Newton's theory was abandoned, mainly for two reasons. The phenomena of refraction could only be explained by it on the assumption that the corpuscles travelled more quickly in dense media than in air, and this, always improbable, was eventually disproved. On the other hand, the theory failed to explain the phenomena of interference and diffraction of light, except by the addition of so many arbitrary supplementary hypotheses, that, in the end, it was borne down by the weight of its own superstructure.

This illustrates a case, oft recurring, not only in the realm of science, where men have been deceived and led to form opinions wide of the truth through the agency of certain resemblances to that truth. The corpuscular theory of light was put aside, but not before it had appreciably retarded the progress of science. The master-mind, the originator of the theory, had been withdrawn before altered circumstances and increased knowledge reversed the weight of evidence. He who would have been the first to detect the want of harmony, the first to move on to new conceptions in the search for truth, by the irony of fate, became for a time, in virtue of his

intellectual supremacy, a stumbling block to his weaker brethren, and an impediment to the cause he had most at heart.

In recent years the discovery of radio-activity has revealed to us particles very like those that Newton used to explain ordinary light. The β rays from radium are projected particles moving with velocities nearly approaching that of light itself. Newton's inscrutable insight, amounting almost to an instinctive knowledge of Nature, has again been demonstrated. His corpuscles cannot, indeed, explain the phenomena of ordinary light; but similar corpuscles we find do exist, and their properties as set forth by Newton are not so unlike those actually occurring in the working of Nature as men have assumed throughout the years which separate the establishment of the undulatory theory of light from the discovery of radio-activity.

The corpuscular theory of light was replaced by a theory of waves in a medium which already had been recognised by Newton as a necessary addition to his idea of corpuscles. Newton's difficulty, which caused him to reject the undulatory hypothesis, namely, the rectilinear propagation of light, and the consequent possibility of sharp shadows, was finally overcome by Fresnel and Young, who showed that shadows were the result of the minuteness of the wave-lengths of light as compared with the dimensions of ordinary obstacles. This cleared the way for the wave theory as already formulated by Huygens, and there arose a definite physical need for the exact specification of an æther or luminiferous medium, pervading all space, and the interstices, if not the substance, of material objects. Such a medium,

indeed, had long been imagined by philosophers, as a means of transmitting actions from one body to another, but its use as a physical explanation of the phenomena of light first indicated some of its necessary properties. The reflection of light from the surface of a glass plate, or its passage through certain doubly refracting crystals, such as tourmaline, modifies the light, which acquires properties not the same on all sides of the emergent beam, and is then said to be polarised. No wave system in which the direction of vibration is in the direction of propagation can show such differences, for in such a system the waves must be alike on all sides of their path. It follows that the luminous vibrations must be transverse to the direction in which the rays are travelling. Transverse waves, if we are to regard them as mechanical motion in a real medium with ordinary dynamical properties, imply a certain amount of rigidity or elasticity of shape in the medium—such elasticity as is possessed by solids alone. No fluid when distorted has any tendency to return to its original form; it cannot transmit waves which depend on mere distortional displacements. Waves in a fluid must be waves of compression and expansion, in which the direction of vibration is in the direction of propagation.

If, then, it is to carry a transverse wave-motion of an ordinary mechanical kind, the luminiferous æther must possess some of the properties of a solid, and at one time the great problem of æthereal physics consisted in formulating a medium possessing the necessary rigidity. Any elastic jelly theory leads to obvious difficulties when the passage of matter through the æther is considered, a passage

which often proceeds with high velocity, but, as far as observation goes, is entirely unimpeded. Rays of light from the stars appear to reach the earth in straight lines, suffering no deflection on passing through the æther outside the atmosphere near the earth. This result suggests that the luminiferous medium is not disturbed by the movement through it of the earth with a velocity of eighteen miles a second—the speed with which the earth moves round the sun. On the other hand, the passage of light over the surface of the earth is not affected by a change in direction relative to the earth's total motion, the velocity of the light is the same whether it is passing with or against the motion of the earth. This result indicates at first sight a conclusion opposed to that formerly reached, and suggests that the æther is at rest relatively to the surface of the earth and is dragged along with the ground as it moves. This seeming discrepancy led at a later date to Einstein's theory of Relativity. The general dynamical problem of constructing a model of the æther on ordinary mechanical ideas of wave propagation never was accomplished satisfactorily during the years when it appeared to be perhaps possible.

As long as the æther was invoked only to explain the phenomena of light, the difficulties of interpretation might well suggest doubts about the fundamental hypothesis as to its existence, but when Clerk Maxwell showed that it was possible to explain the phenomena of the electro-magnetic field by an æther having properties identical with those of the luminiferous medium, the evidence for both theories was strengthened very greatly. Maxwell proved mathematically that the velocity

of an electro-magnetic wave through free space determined the relative magnitudes of certain electric units, so that by comparing the values of the units the velocity could be calculated. Experiment showed that the velocity was the same as that of light; light became an electro-magnetic phenomenon, and optical science a branch of electricity. Many years afterwards, Maxwell's great work was confirmed by the direct experiments of Hertz, who detected the existence, and measured the speed of electro-magnetic waves, thus laying the foundations on which the practical art of wireless telegraphy is based.

Details of the technical applications of science are outside the scope of this work, but a short description of the theory of wireless telegraphy and telephony may not be out of place.

The work of main theoretic interest was done by Maxwell and Hertz, but much development by other men was needed before their achievements could be turned to practical account. The radiation and reception of sufficient energy for signalling at a distance was first made possible by Marconi's introduction of the aerial wire, which is used to emit the waves at one station and catch them at another.

Each single electric spark from an induction coil consists of a few electric oscillations, rapidly dying away. It was these damped oscillations which were used by Hertz and in all the early methods of wireless telegraphy. But nowadays continuous waves, the vibrations of which are maintained constant except when purposely interrupted, are used.

The continuous or undamped waves may be produced by means of what is called a thermionic valve. A hot wire of tungsten, such as is used in electric light bulbs, as explained on page 157, is found to emit negative corpuscles or electrons. Ordinarily, the wire is thus left positively electrified, and, owing to electric attraction, a state of equilibrium is reached and no more electrons are emitted. But if the hot wire be connected with the negative terminal of a battery, and a metal plate within the bulb with the positive terminal, a large continuous negative current will pass from the hot wire to the plate, carried by the continually escaping electrons. On the other hand, if the battery terminals be reversed, no appreciable current will flow, since the electrons now tend to be driven back into the hot tungsten.

Thus the first use of the thermionic valve is as a rectifier. It will allow to pass that half of an alternating current which flows in one direction, and will stop the half which tries to flow in the other.

Next, let a grid, made of a piece of wire gauze, be put between the hot wire and the plate. When the grid is positively electrified, it will help the emission of electrons and increase the thermionic current; when it is negative it will decrease the current. Hence, if it alternate in potential, it will cause the valve of the current to oscillate—in effect superposing an alternating current on a direct or one-directional current. If the primary coil of an induction coil be inserted in the plate circuit, oscillations will be set up in it when the grid potential alternates. These oscillations will be reproduced in the potential at the ends of the

secondary of the induction coil, and, if these ends be coupled back with the grid and the filament in the right direction, the oscillations will give to the grid the proper alternating potential to maintain the oscillations and the plate circuit. The apparatus is thus self-supporting when a current is passed through it, and will continue to produce oscillations, the period of which depends on the induction of the coils and the electric capacity of the system. By adjusting the induction and capacity, the period of the oscillations can be tuned.

Hence a thermionic valve may be used, both to emit continuous waves and to rectify alternating currents when received. By starting and stopping such a train of waves at appropriate intervals, a series of long and short signals may be emitted at one station and received at another in the so-called Morse code.

Continuous waves may also be used to transmit speech by telephony. The alternations of these waves are much too rapid—in the neighbourhood of a million a second—to pass through a telephone or make it sound. But if the currents they produce in an aerial wire be rectified, and then interrupted from 100 to 10,000 times a second, a sound of corresponding pitch is heard in the telephone.

That is the principle of broadcasting speech or other sounds. A steady, continuous undamped wave is emitted from the sending station. This "carrier wave" has some definite wave-length—say 465 metres, which gives a frequency of 645,000 alternations per second.

On this carrier wave, changes and interruptions are superposed by speaking into a microphone connected with the circuit. At the receiving

station, the carrier wave is caught by the aerial wire, and passed through a thermionic valve, which rectifies it, and a telephone, which reproduces the interruptions and variations of the rectified wave as audible sounds.

If we accept the view that an atom is composed of corpuscles or electrons spaced round a nucleus, the electro-magnetic radiation which constitutes light, if it be emitted in accordance with ordinary dynamical principles, might naturally be supposed to take its rise from the accelerations of these corpuscles as they revolve in their orbits, though, as we shall see later, this view has not prevailed in its simple form.

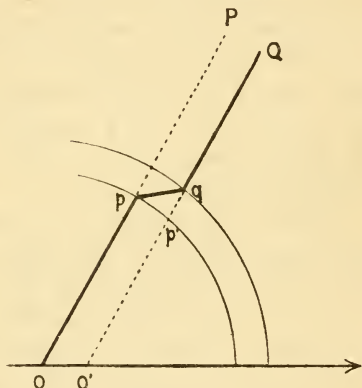


FIG. 36.

Faraday's conception of tubes of electric force, may here be revived in order to explain the radiation of light on the hypothesis of electronic acceleration. As long as an electron is moving forward with uniform velocity, it carries its attendant tubes with it in a steady manner, and no radiation occurs. When it is stopped suddenly, as at the point O in Fig. 36, an electro-magnetic pulse spreads out from it, travelling with the velocity of light. Within the sphere covered by this pulse, a tube of force such as $O\bar{p}$ is stopped, so as to

correspond with the new position of the electron at rest, while outside it, in regions as yet unaffected by the change in velocity, the tube qQ is still moving forward with the original speed of the electron. In the pulse itself, then, the electric tube pq is bent more or less at right angles to the direction of propagation of the pulse, which spreads out from the electron as centre. When tubes move, a magnetic force is produced at right angles both to their length and to their direction of motion; and thus, in the thickness of the pulse, a magnetic force exists, also at right angles to the direction of propagation of the pulse, that is, in the plane of the advancing wave-front, and, in that plane, at right angles to the direction of the electric force. The pulse is thus an electromagnetic disturbance.

Now, if, instead of imagining the moving electron suddenly brought to rest, we suppose that it is reversed in its path, and that this reversal occurs periodically, so that the electron performs simple harmonic vibrations, we get, instead of a single thin pulse, a series of less abrupt but regularly recurring alternations propagated out from the corpuscle as centre. Each Faraday's tube is set into oscillation at its inner end, and transverse waves travel outwards along it, just as waves travel along a stretched cord, when one end is oscillated periodically by the hand. The distribution of electric and magnetic force in the advancing wave-front is exactly the same as in the case of the sudden pulse already studied: we get, in fact, a series of regular æthereal waves, in which there are electric and magnetic forces, both in the plane of the wave-

front, and at right angles to each other in that plane. But such an arrangement is precisely that required to explain the phenomena of light.

In the simple case we have taken, the electron oscillates backwards and forwards in a straight path: the vibrations travel as tremors along the tubes of force in one plane only; the resultant light is plane polarized. In the more general case, we must suppose that the electron oscillates in a circular, or elliptical orbit, and the tubes of force will be displaced in corresponding motions; the tremors running along them will no longer be simple to and fro movements, but points on the tubes will describe curved paths. These paths continually change as the orbit of the electron changes, and we get a more complete model of the propagation of common, non-polarized light.

Faraday's tubes, it is clear, give a very powerful and convenient method of studying the phenomena of the electro-magnetic field, and Thomson has used them in such ways as that just suggested to elucidate modern problems. Indeed it is almost possible that electric tubes of force may represent something more than a useful mathematical fiction. If the structure of the electric field be discontinuous in reality, as our tube-picture of it indicates; if the electric and magnetic effects of a charge of electricity are in reality exerted throughout the surrounding space by means of discrete tubes of force—vortex filaments in the æther, or whatever they may actually be—an advancing wave of light must be discontinuous also. Could we look at such a wave from the front, and magnify it millions of millions of times, we should see, not a uniform field of

illumination, but a number of bright specks scattered over a dark ground. Each tube of force would convey its own tremors, and these would constitute light, but between them would lie undisturbed seas of æther.

Such an idea about the nature of a wave-front of light is very unexpected and surprising. We are inclined at once to relegate our tubes of force to a museum of conceptual curiosities. But it is a remarkable thing that certain evidence in favour of the discontinuous nature of a wave-front of light really does exist. It is impossible to examine the luminous effects with enough magnification to investigate the question, but, as we have seen, ultra-violet light, and still more effectively Röntgen rays, are capable of ionizing a gas through which they pass. Here, it is the molecules of the gas which are affected, and, in examining the ionizing power of the rays, we are in effect using on them a microscope of molecular dimensions.

If the wave-front of a Röntgen pulse were continuous, all the molecules of the gas would be subject to the same disturbance. But, even with the strongest ionizing agency, nothing like one molecule in a million is found to be affected. Thus, if the wave-front be continuous, we must suppose that it is only those very few molecules which are in some peculiarly receptive state that are ionized. The stability of a molecule is greatly affected by temperature, and, if a critical limit of stability were needed for a molecule to become ionized by the rays, we should expect that the ionizing power would increase rapidly with the temperature. Mr M'Clung has shown, however, that temperature has no appreciable

effect. This curious result indicates that the ionizing action is independent of the state of stability of the molecule, and prevents us from finding in this way an explanation of the small number of the ionized molecules in the path of the rays.

It is possible that some other rare condition, unaffected by temperature, may be the necessary preliminary to ionization by incident radiation; but it is also possible that the explanation of the smallness of the ionization is to be sought in the idea that the advancing wave is discontinuous, and is composed of a number of parallel tremors running along discrete tubes of force. The tubes of force being scattered at wide intervals through space, comparatively few molecules would lie in their paths, and only a few would be affected by waves running along the tubes. Matter has been analysed into discrete particles; electricity has been shown to be made up of indivisible units; and now it seems possible that light in physical reality, as well as in text-books of optics, is composed of a number of separate rays. Perhaps there is no need to invent a continuous æther—a system of Faraday tubes radiating from electrons may suffice.

Moreover, serious difficulties have arisen in the interpretation of the facts of radiation. To meet these difficulties we have been forced to regard radiation as emitted not continuously but in discrete units or quanta, just as matter is not continuous but atomic.

In this quantum theory, Thomson finds a place for Faraday's tubes. He regards the electrons in his model of the atom, described on page 216, as

linked to the nucleus by tubes of force. A disturbance may throw one of the tubes into a loop which may possibly close into an anchor-ring and be cast out into space attended by a train of electro-magnetic waves, as a quantum of radiation. We shall consider the quantum theory more fully below. It forms the most surprising development of modern physical research.

From the time of Maxwell onwards, electro-magnetic considerations have formed an essential part of any theory of the æther. It is certain that luminous and electro-magnetic radiations are essentially the same in kind, and only differ in the length of the waves. We, of course, might have ceased to try to represent the properties of the æther by means of any imaginary mechanical model, and, regarding light as a system of electro-magnetic waves, have pushed the inquiry no further, but, besides the difficulty of explaining the facts of radiation at least two considerations prevented our resting content with a mere series of electro-magnetic equations as a final explanation. While some phenomena may be co-ordinated successfully, no conception is thus given of the nature of a static electric charge, or of an ordinary electric current, and there seems, on this mode of representation, no means of attacking the problem of the nature of gravitation, which, it was thought, must some day be explained in terms of the universal medium, if that medium was to survive as a permanent conception in physical science.

Attempts were, therefore, often made to describe ideal models which should represent the

properties of the æther by familiar mechanical conceptions. But it was realised that, even if such a model were successfully constructed, it would not necessarily represent the actual structure of the æther ; that was not its object. The primary function of such a model would have been to justify our theory of the æther as expressed in Maxwell's electro-magnetic equations, in the other equations requisite to explain electric charges and currents, and, if possible, to suggest an explanation of gravitation also.

And so a tendency arose to give up the old elastic solid view of the æther, and to secure the necessary rigidity in another way. A top when spinning possesses rigidity of position. It maintains its vertical position against the effects of its weight, and any displacement from the vertical is followed by definite oscillations around the mean position. These phenomena can best be studied in the gyroscope, which first found a practical application in the Whitehead torpedo, where a direct course is kept by the tendency of a spinning wheel to maintain its axis of rotation undeviated. On these principles, Lord Kelvin and others described a gyrostatic æther, in which the rigidity is secured by the motion of some still more primal material. The æther was perhaps composed of a number of interlacing vortex filaments ; its structure might be fibrous like that of a bundle of hay.

Following the line of thought indicated by Lord Kelvin with his conception of the vortex atom, we conceived matter to be an æthereal manifestation. But the simple vortex ring itself soon failed to meet the demands made upon it.

"The fluid vortex atom," said Larmor, "faithfully represents in many ways the permanence and mobility of the sub-atoms of matter; but it entirely fails to include an electric charge as part of their constitution. According to any æther theory, static electric attraction must be conveyed by elastic action across the æther, and an electric field must be a field of strain, which implies elastic quality in the æther instead of complete fluidity: the sub-atom with its attendant electric charge must therefore be in whole or in part a nucleus of intrinsic strain in the æther, a place at which the continuity of the medium has been broken and cemented together again (to use a crude but effective image) without accurately fitting the parts, so that there is a residual strain all round the place."

It will be noted that any such theory, by which matter, the subject of experimental mechanics, is explained as an æthereal manifestation, changes the point of view from which we regard mechanical models of the æther itself. Æther, being now regarded as a sub-material medium, is not necessarily described by the experimental laws to which the facts of ordinary mechanics conform. In dealing with the æther, we are on an entirely different plane, and have no right to assume that a mechanical model of its properties is possible—strictly speaking, the mere statement in mechanical terms of the problems involved may be in itself misleading.

However that may be, on this theory the corpuscle of J. J. Thomson, the electron of Stoney, Larmor, and Lorentz, was represented in the æthereal world by Larmor's conception of a centre

of intrinsic strain. Unlike the vortex atom, this strain-centre is not a part of the medium for ever separated from the rest ; the strain alone persists, the part of the æther which is affected by it constantly changes as the sub-atom is moved. The æther is stagnant, and the sturdy ghosts which constitute matter float to and fro through it as waves pass over the surface of the sea. Such a persistence in time with mobility in space would be impossible for a strain-form in any elastic solid æther, but can be secured by a rotational æther of the type described by Lord Kelvin.

According to this view, then, an electron or unit charge of electricity is a centre of intrinsic strain, probably of a gyrostatic type, in an æther, which is also the medium in which are propagated the waves of light and wireless telegraphy. Moreover, the electron is identical with the sub-atom which is common to all the different chemical elements, and forms the universal basis of matter. Matter, at any rate in its relation to other matter at a distance, is an electrical manifestation ; and electricity is a state of intrinsic strain in a universal medium. That medium is prior to matter, and therefore not necessarily expressible in terms of matter ; it is sub-natural if not super-natural.

To reduce all physic to a theory of the æther as described above is a bold attempt to achieve uniformity. Twenty years ago it seemed almost on the threshold of success. But since then science has developed along other lines, which we shall trace on future pages. For these developments it has proved unnecessary to invoke the idea of a universal æther. For the time, at all events, the tendency is to ignore the problem of the

æther, perhaps partly owing to the great difficulties of interpretation which we shall describe presently.

Nevertheless, from the theory of radiation, as well as from Thomson's experiments, was reached the conception of an electron theory of matter. Within a few years, experimental confirmations of the fundamental conceptions of that theory gave it a firmer position than could have been hoped at the time the theory was formulated.

The property of mass, the most fundamental property of matter for dynamical science, is explained by the electron theory as an effect of electricity in motion. Forasmuch as a moving charge carries its lines of electric force with it, it possesses something analogous to inertia in virtue of its motion. The quantitative value of this effect has been calculated by Thomson, Heaviside, and Searle. Definite experimental evidence was first given by Kaufmann, who found that the ratio e/m of the charge to the mass for the corpuscles ejected by radium diminishes as their velocity increases. The charge is almost certainly constant, and thus the mass must increase with the velocity. Theory shows that, for a slowly moving corpuscle, the electric inertia outside a small sphere of radius a , surrounding the electrified particle, does not depend on the velocity, and is measured by $2e^2/3a$ where e is the electric charge on the particle. But when the velocity of light is approached, this electric mass grows very rapidly; and, on the assumption that the whole of the mass is electrical, Thomson calculated the ratio of the mass of a corpuscle moving with different speeds to the mass of a

slowly moving corpuscle, and compared these values with the results of Kaufmann's experiments.

Velocity of Corpuscle in Centimetres per Second.	Ratio of Mass to the Mass of a slowly moving Corpuscle.	
	Calculated.	Observed.
2.36×10^{10}	1.65	1.5
2.48×10^{10}	1.83	1.66
2.59×10^{10}	2.04	2.0
2.72×10^{10}	2.43	2.42
2.85×10^{10}	3.09	3.1

In this remarkable manner was it possible to show that the electrical theory of mass is in accordance with these striking and unexpected experimental results. Nevertheless, as we shall see later, the same consequence of high velocity in changing mass may be shown to be a deduction from the theory of relativity, without invoking electric conceptions.

We must now return to the story of the modern atom, which we left to give an account of the facts of radiation and the theory of a luminiferous æther. To explain all the properties with which we know the chemical atoms to be endowed, and more especially their power of complex radiation, a theory has been built up during recent years, chiefly by Thomson, Rutherford, and Bohr, which represents an atom as a structure containing one or more electrons in orbital motion round a centre. It would be difficult to explain such results if the electrons were crowded together; thus it seems necessary to suppose that

the electrons occupy an exceedingly small fraction of the whole volume of the atom, just as the planets occupy a very small fraction of the space comprised within their orbits.

The mass of the electron being electrical in its nature, we may calculate the size of the individual electrons or corpuscles from the expression $2e^2/3a$ for the electrical mass. We know the values of e and of e/m , and from these results we calculate a to be about 10^{-13} centimetre. According to Thomson, a is the radius of a sphere outside which the momentum of the electric field exists. It seems reasonable to identify this sphere with the effective dimensions of the electron itself.

We have already seen that, in a substance like water, where the molecules are packed fairly closely, 1 cubic centimetre contains about 3×10^{22} molecules, or, let us say, 10^{23} atoms. Along each edge of the centimetre cube about 4×10^7 atoms are ranged, and thus we may take the effective radius of an atom to be about 5×10^{-8} of a centimetre. Its volume would be about 10^{-23} of a cubic centimetre, while the volume of an electron, according to the above estimate of the radius, is about 4×10^{-39} . Thus, while the diameter of an electron is less than the hundred-thousandth part of that of an atom, the volume of an electron is only about the 10^{-16} part of that of an atom, and their relative sizes might be compared by the illustration of a fly roaming about inside a cathedral.

On the planetary theory of the atom, the moving electric charges produce a magnetic field, just as does a current flowing round the coils of a galvanometer. Thus, conversely, an impressed magnetic force should modify the movement of

the electrons, and affect their radiation, which depends on the rate of acceleration of their motion. The theory of this effect was considered by Lorentz and Larmor, who predicted the subdivision of the spectral lines, afterwards experimentally discovered by Zeeman.

The connection of the electron theory with the phenomena of radio-activity has already been considered in the aspects which were first appreciated. The conception of an atom as a system of electrons in rapid orbital motion naturally suggests its occasional disintegration; indeed the possibility of such disintegration had been treated as a difficulty of the theory by Larmor before the discovery of radio-activity directly indicated its occurrence. But we now know much more about the *modus operandi* of atomic disintegration, and have discovered that the changes concerned in radio-activity have not to do with planetary electrons, but with a much more deep-seated and essential part of the atom, its nucleus.

The first step in the formulation of the modern theory of the atom was the discovery of the electron, the negative electric unit. The second step was the recognition of a positive nucleus. This step was taken by Rutherford.

The α particles, as we have seen on page 193, are helium atoms projected with high velocities. Their mass is four times that of a hydrogen atom, that is, 4×1850 or 7400 times the mass of an electron. The forces exerted on α particles by electrons would be much too small to affect their paths appreciably. And most α rays, it is true, pursue a straight path through matter. Yet here and there one is

found to be hurled aside as by a mighty force. Rutherford examined this scattering of the α particles, and found that it would be accurately explained if we suppose that the atoms of the gas through which they passed were formed of electrons revolving about a central, very minute, but relatively massive nucleus with a positive charge, which repelled the flying positively electrified α particles as they passed, in the orthodox manner according to the inverse square of the distance, and thus swung them aside in hyperbolic orbits.

Since the electrons are of negligible mass compared with the nucleus, the mass of the nucleus is very nearly the atomic weight of the atom. Thus the mass of the uranium nucleus is about 238 times that of the nucleus of hydrogen. The size may be estimated by measuring the amount of scattering of α particles by different atoms at large angles. A heavy atom seems to have a nucleus with a radius not greater than 6×10^{-12} centimetres and those of light atoms would be yet smaller.

The electric charge on the nucleus may also be estimated by a study of the same scattering effect. It seems to increase with the place of an atom in the periodic table. But this fundamental result was first discovered, and has been most satisfactorily demonstrated by another line of research.

As we saw on page 139, the X-rays discovered by Röntgen have been proved to consist of waves similar in kind to those of light, but of very much shorter wave-length and greater frequency of vibration. Their wave-lengths may be measured by analysing them by a crystal, the layers of molecules in which act towards X-rays as the parallel

scratches on a diffraction grating act towards light, separating the waves, and spreading them out into a spectrum.

Now X-rays are produced by the impact of cathode rays on solid obstacles, and it is found that the wave-lengths of the X-rays so produced depend on the nature of the target exposed to the cathode rays. Generally there is a certain amount of diffuse radiation, mixed with rays of definite frequency and wave-length corresponding to the line spectra of visible light.

The spectra from these characteristic X-rays were examined in 1913 and 1914 by H. G. J. Moseley, who directed the rays from different elements, when used as cathode ray targets, successively on to the surface of a large crystal of potassium ferrocyanide to serve as a grating. The resulting line spectra when photographed and measured showed a surprising regularity. Similar groups of lines are found in the spectra of different elements, and Moseley discovered that the square roots of the frequency of vibration of the chief lines in each X-ray spectrum increased regularly by a constant amount as he passed from element to element in the periodic table. By adjusting the constants, this constant difference can be made equal to unity, and Moseley was thus able to assign to each element an atomic number, representing its true place in the periodic table which begins with hydrogen = 1.

On the nuclear theory of the atom, the frequencies of vibration must depend on the electric charge on the nucleus, and Moseley concluded that the atomic number also represented the number of electric units in the charge

on the nucleus. This conclusion is supported by the estimation of nuclear charges obtained from the scattering of α rays and is now fundamental in modern physics.

Moseley's atomic number is a constant for each element more important even than the atomic weight. It gives a new base for the periodic table, founded on known physical principles instead of on mere empirical observation. By its means, we can obtain values for the most important property of an atom, its nuclear electric charge, and thus start on new investigations into the fascinating problem of atomic structure.

The fact that α rays are flights of helium atoms, shows that the atomic break-down which accompanies radio-activity is an affair of the nucleus, and not a mere ejection of some of the outer planetary electrons. It shows, too, that nuclei are constructed partly at all events of helium. Yet the mass of the helium atom is almost exactly four times that of the hydrogen atom—a fact which can hardly be mere coincidence.

If we make the simplest assumption, and regard the lightest atom, that of hydrogen, as made up of a positive nucleus with one revolving negative electron, we shall find it in accordance with all the evidence given above or following below. The electron is the fundamental negative unit, and the hydrogen nucleus, or proton, is the corresponding ultimate positive unit. From these two opposite units, all matter seems to be made up.

Helium, with atomic number 2 and atomic weight 4, must have 2 units of charge on its nucleus, and therefore, in its neutral form, 2

attendant planetary electrons. Its nucleus must, therefore, be made up of 4 hydrogen nuclei or protons bound together by 2 nuclear negative electrons. Since this nucleus holds together during its violent projection as an α ray particle, its structure must be very stable—no power on earth seems able to break it up once it is formed. As a secondary unit, it enters into the making of other more complex nuclei. With atoms the atomic weight of which is divisible by 4, there is no reason to suppose that any more fundamental building materials than helium nuclei bound together with electrons are used. But atoms such as nitrogen, atomic weight 14, or aluminium 27, cannot be so constructed. As Rutherford has found by experiment (see page 201) they contain also hydrogen nuclei. Nitrogen, we may suppose, is made of 3 helium nuclei, $3 \times 4 = 12$, and 2 hydrogen nuclei each weighing 1, that is, 14 in all. Atoms are probably built up, as far as may be, of helium; the odd corners are filled in with hydrogen, and the whole bound together with the necessary electric mortar of negative electrons. Round this complex nucleus, which has an excess positive charge indicated by the atomic number, electrons revolve as planets round the sun, the number of negative electrons being equal to the net positive charge on the nucleus. Thus an atom of uranium, atomic number 92 and weight 238, would be composed of 59 helium and 2 hydrogen nuclei, bound together with 146 negative electrons into a central mass, round which 92 electrons revolve.

These attendant electrons must in some way give rise to electro-magnetic radiation, and, since

we find two such differing types of radiation as heat and light on the one hand and X-rays on the other, we may well guess that the many planetary electrons revolve in different rings, X-rays coming from the inner, and heat and light from the outer rings. This guess has been abundantly supported by evidence in more recent research.

Hitherto, wonderful as are the results described, they involve no breach with the old and well-tried principles of Newtonian dynamics. The paths of α particles, deflected by atoms of a gas, show the law of inverse squares, and the atomic corpuscles whirl round in their orbits as the planets round the sun. But, if we push our analysis further, we find that we are forced to assumptions which are not in accord with this familiar scheme of science. We are brought to contemplate conditions which we cannot explain on any known principles, conditions which, in the present state of knowledge, seem not only inexplicable but inconceivable to our minds. It may be that future years will see these difficulties resolved by human insight as so many others have been. But we must not overlook the possibility that the orderliness we perceive in nature may be merely the rediscovery of conventions we have ourselves inserted when framing the problems to be investigated. We choose mass and energy as convenient fundamental physical quantities. But, all unconsciously, this choice is made because mass and energy happen to remain constant throughout a series of physical and chemical changes—and then triumphantly we

rediscover the persistence of matter and the conservation of energy. As Professor Eddington disturbingly suggests, every law of nature which seems to us rational may be a concealed convention which we have ourselves unconsciously inserted. Hence an unavoidable conclusion which yet seems to us irrational may be the sign of transcendent importance—the sign of a real law of nature at last. If so, we seem almost brought back to Tertullian's *credo quia impossibile*.

The new outlook on physics was first suggested to Planck by the facts of radiation. If the æther be continuous, all radiant energy must pass from matter to æther, just as the energy of floating bodies set in vibration passes into the surrounding water. If we are to hold any mechanical view of the æther, we must therefore consider that it too possesses a structure, though probably much finer than that of matter. Even if we take it as of the same order of fineness as that of matter, mathematical calculation shows that most of the energy radiated by matter should be concentrated in the short wave-lengths of the ultra-violet light. But observation shows that in a continuous spectrum, such as that of the sun, the maximum heat effect, which measures the total energy, is in the infra-red, that is, in those waves too long to affect our eyes instead of in those too short.

To meet this difficulty Planck, in 1901, supposed that radiation was emitted and absorbed by matter not continuously but in small indivisible units. To calculate the rate of emission of energy then becomes an exercise in the theory of probability—how many units are likely to be

absorbed or emitted in a given case. With quite reasonable assumptions, this statistical method accounts for the facts it was framed to meet.

But most theories can do as much as that. The real test comes when a theory is extended to cover other facts which were not in mind during its inception. Hence the evidence for the quantum theory was much strengthened when Einstein, in 1907, applied it successfully to explain the fact that the specific heats of certain solid elements like carbon, and other elements at low temperatures, were not constant, as classical physics required, but varied with temperature. If energy be absorbed not in infinitely small quantities but by finite units, we can explain this result, for when temperature is low and heat units scarce, some atoms will possess no units at all, and thus the total content of energy, and therefore the specific heat, is small. A mathematical investigation shows that the expected change of specific heat with rising temperature is in accurate accordance with observation.

To fit in with the numerical results, the unit of energy ϵ must be equal to $h\nu$, where ν is the frequency of vibration and h a constant called Planck's constant, which has the value 6.5×10^{-27} erg-seconds. It will be seen that the size of the units of energy depends on the frequency of vibration, and is larger when that frequency is great, as in violet and ultra-violet light, than when the frequency is small and the wave-length large, as in red light or invisible radiant heat.

The real constant is Planck's quantity $h = \frac{\epsilon}{\nu}$, which is not energy, but energy divided by

frequency. Since frequency is a number of vibrations in a given time, it follows that Planck's constant is energy multiplied by time. This quantity is of fundamental importance in modern physics and is called *action*.

A unit of energy multiplied by the time during which it is applied is called a unit of action, and Planck's constant h is the natural, real unit of action, just as the electron is the natural real unit of electric charge or of mass.

We are now ready to take up again our story of the development of the modern theory of the atom where we dropped it on page 244. We had then reached the conception of a central nucleus, made up of a conglomerate of positively electrified helium and in some cases hydrogen nuclei cemented together with negative electrons, and surrounded at great comparative distances by attendant rings of other revolving planetary electrons. As the simplest assumption, we supposed that the hydrogen atom, the lightest known to us, was a central positive unit particle or proton, with one planetary electron.

Now the spectrum of hydrogen is of considerable complexity. It is not continuous, not a uniform band of coloured light like the rainbow, but it consists of sharp lines many in number.

An electron revolving round a nucleus would, as we saw on page 149, on any classical electrodynamic theory, emit electro-magnetic radiation. It must thus lose energy, fall nearer the nucleus, and swing round it with steadily increasing velocity. A collection of atoms of hydrogen,

then, should emit radiations of all frequencies of vibration, that is, should give a continuous spectrum.

Hence we see that the existence of line spectra, not from hydrogen merely but from many other elements, again leads us to contemplate the difficulties of Newtonian dynamics applied to electro-magnetic atoms, and once more brings us to some form of quantum theory.

The application of these conceptions to the problems of atomic structure was first made by Niels Bohr of Copenhagen, then working in Rutherford's laboratory at Manchester.

Certain regularities in the complex spectrum of hydrogen become apparent if we consider not the wave-lengths of its luminous lines but the number of waves in a centimetre—a quantity which may be called the vibration number. It is found that the vibration numbers of all the lines may be expressed as the difference between two terms. There is first a fundamental term, called Rydberg's constant, after its discoverer; its number is about 109700 waves per centimetre. Other terms are obtained from it by dividing it by four (2×2), nine (3×3), sixteen (4×4), and so on. If we subtract these terms from R , Rydberg's constant, we get vibration numbers, $R - \frac{R}{4} = \frac{3}{4}R$, $R - \frac{R}{9} = \frac{8}{9}R$, etc., and these numbers correspond to hydrogen lines in the ultra-violet. If we begin with the first derived term, that is one-fourth of 109700 or 27425, and subtract the higher derived terms from it, we get another series of numbers, $\frac{R}{4} - \frac{R}{9} = \frac{(9-4)R}{36} = \frac{5}{36}R$, etc.,

corresponding to the visible lines of hydrogen known as Balmer's series. Another group, obtained from one-ninth of 109700, was found in the infra-red by Paschen.

These relations were discovered by making experiments, and then guessing at arithmetical rules till one was found to fit the facts. They are purely empirical. But Bohr saw how to explain them all by applying Planck's quantum theory to the atom.

Bohr pointed out that, if "action" is absorbed only in units, of all conceivable orbits in which the hydrogen electron might revolve, only a certain limited number would be possible. In the smallest orbit, the action would be one unit or h , in the next orbit $2h$, and so on. Mathematical investigation shows that the energy of motion in the second orbit is a quarter that in the first, in the third orbit one-ninth, and in the fourth one-sixteenth.

As an electron falls in from an outer to an inner orbit, it loses energy of position and gains energy of motion. It may be shown that the total loss of energy is equal to the gain in energy of motion. Hence, if ϵ be the energy of motion in the first or smallest orbit, it follows that, in passing from the second orbit to the first, the loss of energy

is $\frac{3}{4} \epsilon$, in passing from the third to the second,

$\frac{8}{9} \epsilon$, and from the third to the first, $\frac{1}{4} - \frac{1}{9}$ or $\frac{5}{36} \epsilon$.

It will be seen that this series of numbers is the same as that found experimentally in the vibration numbers of the hydrogen spectrum.

On this evidence Bohr founded his theory of the hydrogen atom. He supposes that the

hydrogen electron has four possible stable orbits, corresponding to successive units of action. Here we leave Newtonian dynamics. A planet can revolve round the sun in any one of an infinite number of orbits, the actual path being adjusted to its velocity. But an electron can only move in one of a few paths, each of which corresponds to an integral number of units of action. If it leaves one such path, it must jump instantaneously to another, apparently without passing over the intervening space. Perhaps there is no intervening space: perhaps space, perhaps even time, is discontinuous. But that is another story.

When the electron leaps from one stable path to another it radiates energy $h\nu$, the action of which is h , and the frequency of vibration ν . The energies lost in the changes described above are $\frac{3}{4} \epsilon$, $\frac{8}{9} \epsilon$, $\frac{15}{16} \epsilon$, etc. Hence, since h is constant, the frequencies ν_1 , ν_2 , ν_3 , etc., must be in the ratios $\frac{3}{4}$, $\frac{8}{9}$, $\frac{15}{16}$, etc., and we get the known series of lines in the hydrogen spectrum. It is possible, furthermore, to calculate the numerical value of the fundamental term corresponding to Rydberg's constant, and to reach the amazing result that it agrees with the figure on page 248, as obtained by observation. Even more complex phenomena of the hydrogen spectrum are fully explained by Bohr's theory as developed by Sommerfeld, and it is impossible to doubt that we are on the right road. Hydrogen atoms must be something like Bohr's picture of them. Heavier atoms with more planetary electrons give problems beyond the present power of mathematical analysis. But

what progress can be made on the general lines of Bohr's theory is all consistent with observed facts.

Here, then, in the quantum theory and Bohr's application of it to atomic structure, we have quite a new departure in science. No explanation can be given at present on the principles of classical dynamics of the existence of an indivisible quantum of action, or of its consequence the restriction of atomic planetary electrons to a few definite orbits. The quantum seems a brute fact, which we must accept, but cannot, yet at any rate, explain. But this, as Eddington holds, may be a sign of its real importance. It is certain that we ourselves have not read it into the story of Nature.

We must now pass to the consideration of the theory of relativity, which has shared with the theory of quanta and the allied problem of atomic structure the chief attention of mathematical physicists during recent years.

The idea of relativity arose from the results of various measurements of the velocity of light, and the discordant indications they gave of the relation between the earth and the hypothetical æther of space.

Astronomical observations suggest that the earth moves through a quiescent æther, the æther streaming through the moving atoms of matter as wind through a grove of trees. Moreover, Lodge found that the velocity of light between two parallel steel discs, whirled round their axis at great speed, was the same whether the light passed in the same or the opposite direction to the movement of the plates. In this case, the

steel seems to exert no drag on the æther just outside it.

On the other hand, a classical experiment made in 1887 by the American physicists Michelson and Morley, indicated a contrary result. If the æther is quiescent, as the earth moves through space there is relative motion between it and the æther, and a stream of æther must pass through a laboratory.

Now a swimmer can pass across a rapid river and back again quicker than he can swim an equal distance up and down stream. Hence a ray of light should take longer to pass along the æther stream and back from a mirror, than if it travelled at right angles to its first path and were reflected back from across the stream.

When Michelson and Morley carried out this experiment, they found to everyone's surprise that no difference could be detected.

Of course they could not know beforehand in which direction the æther was moving through their laboratory, but by rotating the apparatus into another position, and trying the experiment at different seasons of the year, they got over this difficulty. But the two rays, at right angles to each other, one going across and one along the stream, always arrived at the observation post together—the race was always a dead-heat, however the apparatus was placed and whatever were the time of year.

This experiment has been repeated in more recent years to a higher order of accuracy with the same result. It clearly indicates that the measured velocity of light is the same when travelling with and against the motion of the

earth. It suggests that the æther is carried along with the earth, a conclusion apparently inconsistent with the astronomical evidence.

The first successful attempt to explain this discrepancy was made by Fitzgerald, Lorentz, and Larmor. If the atoms of matter are electrical in nature, or held together by electrical forces, it is possible that matter may contract when it is moving through the electro-magnetic medium or æther. A very small contraction when matter is moving through æther would suffice to explain the facts, and the contraction could never be observed directly, for all scales used to measure it would undergo the same proportionate change. It is probable that this explanation represents one aspect of the truth. However this may be, the velocity of light, as experimentally measured by an observer, has always been found to be 3×10^{10} centimetres, or 186,000 miles a second.

Impressed by this experimental result, Einstein, in 1905, accepted the constancy of the measured velocity of light as an ultimate fact of Nature, and was hence led to see that real experimental space and time are always relative to some observer, and that the ideas of absolute space and time are mere figments of the imagination.

By length or distance we always mean a quantity arrived at by measurements made with material or optical appliances by some particular observer. Thus, we see that the length of a rod is not an absolute property of the rod, but is a relation between the rod and the observer. If they are moving together, the length seems invariable, but, if the rod is moving past the observer, it suffers the contraction suggested by

Fitzgerald. The time-scale undergoes a corresponding change. A clock, to an observer moving with it, goes steadily, but, if it were carried past the observer at great speed, it would seem to slow down.

But, while both space and time separately are relative to the observer, Minkowski, in 1908, pointed out that there is a combined space-time which is absolute: a space-time of such a nature that the velocity of light is a true natural constant. Hence, instead of the familiar three dimensions of space, length, breadth, and height, with time as a completely independent quantity, we must add time as another dimension, and picture the universe in terms of an inseparable space-time involving four dimensions. Any given particle is moving through both space and time. The distance it moves depends on the observer, and the time it takes to traverse that distance depends on the observer, but its track through four dimensional space-time, what is called the "interval" between its first state and its last, does not depend on the observer, but is the same for all observers—a true characteristic quantity for the particle.

Since clocks are timed by pendulums or heavy balance wheels which possess mass, the slowing down of time suggests that mass, like length and time, changes with the observer, and that the mass of a fast moving body becomes greater to an observer at rest. The amount of this increase may be calculated from Minkowski's space-time "interval" which we have just described. The velocity of a body may be written as $v = l/t$, where l is the length described in a time t . But, if instead of t we write the

“interval” s , we get a new kind of velocity l/s . Similarly momentum, which in the old mechanics is Mv or $M \cdot l/t$, mass multiplied by velocity, may be modified into a new kind of momentum, $m \cdot l/s$. Here m is constant. But in physics it is, for the present at all events, more convenient to keep to the old definition of momentum as mass and velocity. We then have—

$$m \frac{l}{s} = m \frac{t}{s} \cdot \frac{l}{t} = M \frac{l}{t},$$

where $m \cdot t/s$ is a modified mass, M , identical with our old mass, no longer constant but dependent on the motion through the observer's space and time. It is easy to show mathematically that, if momentum is conserved,

$$M = \frac{m}{\sqrt{\left(1 - \frac{v^2}{c^2}\right)}}$$

where c is the constant velocity of light.

This is the same law of increase that was calculated on the electro-magnetic theory by Thomson, and verified by the experiments of Kaufmann and others on β particles (page 237). We now see that, while consistent with, it does not necessarily verify, the electrical theory of matter, since it follows also from the general theory of relativity. If the observer moved with the β particles, their mass as measured would of course remain constant. The change is a consequence of the relative motion.

The last equation can be put in the form—

$$M = \frac{m}{\sqrt{\left(1 - \frac{v^2}{c^2}\right)}} = m \left(1 - \frac{v^2}{c^2}\right)^{-\frac{1}{2}}.$$

Since the velocity v of a moving body is usually small compared with the velocity c of light, this result gives—

$$M = m \left(1 + \frac{1}{2} \frac{v^2}{c^2} \right) = m + \frac{\frac{1}{2} m v^2}{c^2}$$

That is, the effective inertial mass of a moving body is its mass at rest plus its kinetic energy $\frac{1}{2} m v^2$ divided by the square of the velocity of light. It seems that mass is of the nature of energy or energy of the nature of mass: matter and energy may be identified.

From this result it seems reasonable to suppose that a region filled with any form of energy, even for instance light or radiant heat, would possess inertia equal to the energy contents divided by the square of the velocity of light. It does not immediately follow that the energy would be subject to gravitation. It may possibly be that the equivalence between mass and weight, proved experimentally by Galileo and Newton, applies to m in the equation, to the mass at rest, and not to M which contains also the kinetic energy. The problem of gravitation needs further consideration.

The principle of relativity was first applied to the phenomena of gravitation by Einstein, in 1911. He pointed out that it was impossible by any experiment to distinguish a gravitational force from the force experienced by an observer who is accelerated, that is, whose motion is changing. For instance, when a lift starts to rise, the occupants feel all the effects of a sudden

though temporary increase of weight; indeed, a mass hung from a spring balance would weigh heavier till the upward speed of the lift became uniform. Einstein assumed that this principle of equivalence held not only for mechanical but also for electrical effects, including light.

The application of these ideas involved great mathematical difficulties, and Einstein did not publish a full account of his researches till 1915. It then appeared that many of the theories of the older physics, including Newton's law of gravitation, might be replaced by new explanations of the phenomena.

Mathematical analysis shows that the space and space-time of Einstein and Minkowski have certain peculiarities. At places they are impenetrable, and there we may fairly suppose to exist what we call particles of matter. Near these places the equations show that space and space-time are subject to what in a line or a surface we call curvature. How three dimensional space and four dimensional space-time can be curved, we must imagine as best we may. The wonders of nature are not necessarily comprehensible to our minds.

The curvature of space and space-time may perhaps best be left in the decent obscurity of mathematical equations. The equations show that the natural path of a particle of matter traversing a region near a massive body is not the straight line passed over with uniform speed contemplated by Newton's First Law of Motion, but a path in space-time that bends towards the mass in space, and in time moves faster the nearer it passes to the matter—the path, in fact, of a planet swinging round the sun.

Thus the effect of the sun, which for two hundred years and more has been referred to an attractive force between the sun and the planet, can be explained as due to a curvature in space, which makes the natural path of the planet when undisturbed an ellipse instead of a straight line. If a body be falling freely, and so following its natural path, it feels no sensation of force. If it be prevented from falling by a chair or the platform of a weighing machine, it is turned from its natural path and shows the phenomenon we call weight, which may be regarded as due to the upward acceleration impressed on the body by the bombardment of the molecules of the chair or the platform.

The mathematical theory shows that all the long known facts of gravitation can be deduced equally well from Newton's theory or Einstein's principle. Yet three phenomena have been found in which, when great accuracy of observation is reached, differences should appear and crucial experiments be possible.

(1) A minute divergence of the planet Mercury from its Newtonian path—a divergence only amounting to 43 seconds of arc in a century—was at once explained by Einstein.

(2) Both on Newton's theory and on Einstein's, the path of a ray of light, passing near a massive body like the sun, should be bent towards the body, but Newton's deflection is one half that of Einstein. The only way of observing this deflection is to measure accurately the apparent position of the image of a star very near the sun on a photographic plate exposed during an eclipse. This was done in two places, Sobral in Brazil and

the Island of Principe in the Gulf of Guinea, on 29th May 1919. The result was in accordance with Einstein's prediction.

(3) On the principle of relativity, the electrons in a gravitational field should vibrate more slowly than the normal. Hence the lines in the spectrum of the sun, where gravity is strong, should be slightly shifted towards the red. For long this effect was looked for in vain, but lately evidence in its favour has been obtained.

The balance of experimental evidence, then, leans decidedly towards Einstein's interpretation of nature, or possibly some modification of it such as that put forward by Professor A. N. Whitehead, and we must learn to regard as merely relative, many concepts we had come to accept as absolute.

Doubtless this new outlook has not only a physical but also a philosophical importance. Space and time no longer exist independently of each other and of events which happen. Nature is a complex continuum, in which matter, space, and time are all inextricably involved. The separation is no more than a question of human convenience like the separation of science into physics, chemistry, and biology. Many of the familiar concepts in which, first by the ordered common sense of successive generations of men, and then by the more subtle analysis of science, we had come to express our mental picture of the world, have been proved to be merely relative to ourselves. The length of a rod, the time beaten out by a pendulum, the mass of a chemical atom, so constant and absolute to our fathers, are now seen to be relations between us and the body

observed, no more essentially constant than the value of gold to a mariner when in New York at one time and on a desert island at another.

Much of our old scheme of science has been put into nature by our own minds, and then rediscovered. Possibly that is why nature has seemed to us to be rational. We are beginning to fear that things too easily rationalised are but the delusive image of ourselves seen in nature's mirror. The real nature may have but little in common with that looking-glass world. Yet one quantity stands out, at present incomprehensible, with all the signs of a real natural constant—the unit of action in Planck's great quantum theory.

CHAPTER IX

ASTRO-PHYSICS

For who so list into the heavens looke,
And search the courses of the rowling spheares,
Shall find that from the point where first they tooke
Their setting forth, in these few thousand yeares
They all are wandred much ; that plaine appears :

Ne is that same great glorious lampe of light,
That doth enlumine all these lesser fyres,
In better case, ne keepes his course more right,
But is miscaried with the other Spheres :
For since the terme of fourteene hundred yeres,
That learned Ptolomæ his hight did take,
He is declyned from that marke of theirs
Nigh thirtie minutes to the Southern lake ;
That makes me feare in time he will us quite forsake.

—SPENSER, *The Faerie Queene*, Book V.

THE origins of the ancient science of astronomy are lost in the mists of the past. Unlike some of the subjects we have discussed in this volume, its phenomena are familiar to the most unobservant of mankind, and some of these phenomena, in the apparently unfailing regularity of their manifestation, have served as measurers of time and forewarners of seasons during immemorial ages.

The recognition of the possibility of slow change in this regularity, and the attempt to detect such change by careful observation, are also an old story, while unusual manifestations, such as comets and eclipses, were, till comparatively recent

times, regarded with fear and consternation, and considered as direct signs of Divine wrath.

Yet the oldest of the sciences is also, in some respects, if not the newest, at any rate among the youngest of the fraternity; for in its recent growth, its spirit of adventure, its capacity of immediate development, it shows all the characteristics of sturdy youth.

In the history of the different branches of physical science, it is constantly found that periods of great activity and advancing knowledge alternate with periods when, owing to the exhaustion of the possibilities of the apparatus available or of the methods of research employed, progress seems almost to cease.

Seventy years ago astronomy appeared to be sinking into one of these periods of comparative stagnation. The power of the telescope seemed almost to have reached a limit, for although improved and larger instruments were being produced continually, the revelations they made were apparently unworthy of the knowledge and skill lavished on their manufacture. It was not more elaborate instruments, but new methods of research that were wanting.

But even while the older astronomy was flagging, the new method had appeared, and was only waiting for development in its apparatus to carry forward the torch of learning into untrodden paths, and even to rival the discoveries of Adams and Leverrier, who had stirred so profoundly the imagination of their generation.

The new science of astro-physics dates from the application of the spectroscope to astronomical

problems. The spectroscope itself illustrates the progressive triumph of modern science, for it is the work neither of one man nor of one century. Its principles have been developed gradually and its construction elaborated throughout a couple of hundred years. Newton was the first to analyse the light of the sun by a prism, to study the spectrum thus obtained, and to show that it consists of rays of every colour, which, when blended together in the eye, produce the sensation of white light. In the year 1802, Wollaston noticed that the spectrum of the sun's light was crossed by a number of fine dark lines, and, shortly afterwards, the relative positions of these lines were mapped carefully by Fraunhofer, whose name the lines have borne since that time.

The next great advance was made by the chemists Bunsen and Kirchhoff, who repeated and amplified, in the year 1860, an almost forgotten experiment of Foucault, though the principles which underlie their discovery had previously been understood by Sir George Stokes. Any vibrating system—a child's swing, for example—is set into violent oscillation if impulses are given to it exactly timed to coincide with its own proper period of vibration. Just as the particular piano wires which are tuned to a particular note will be set in vibration when that note is sounded in their neighbourhood, so the molecules or atoms of a gas will be set in vibration by waves of light which possess a period of oscillation corresponding with their own. A complex wave of light, then, passing through a collection of such molecules or atoms,

will have those constituent waves absorbed which are tuned to the characteristic periods of the absorbing systems. Substances, that is to say, absorb the particular kinds of radiation which they would themselves emit when hot.

Applying these principles to the Fraunhofer lines, Stokes held that when coincidences existed between their positions and those of the bright lines obtained by examining with a prism the light of incandescent vapours, the coincidence was to be interpreted by the supposition that similar vapours were present in the atmosphere of the sun, and absorbed the light coming from the hotter regions below them.

In 1860 Bunsen and Kirchhoff, without knowing that Foucault had anticipated them in 1849, devised and carried out an experiment on the artificial production of Fraunhofer lines. They passed the light of an electric arc, which gave a perfectly continuous spectrum with no such lines as those in the solar light, through the vapour of sodium volatilised in the comparatively cool region of a spirit lamp flame. They had the joy of seeing a black absorption line, coincident with the bright line given by hot sodium vapour, crossing the continuous spectrum of the arc, just as the black line, called by Fraunhofer the line *D*, crosses the spectrum of the sun. The possibility of determining the chemical constitution of the heavenly bodies had opened before the eyes of man.

Hitherto the sun had been studied chiefly in relation to the earth and the general solar system, while little else was known about the stars than their apparent relative positions on

a hypothetical celestial sphere. Their composition and physical condition were held to be outside the range of any definite scientific investigation; subjects, perhaps, better fitted to the romancer than to the serious student. But with the advent of the spectroscope, sun and stars, in a new aspect, re-entered the realm of exact knowledge, and began to give up the secrets of their composition and state.

Many of the chemical elements known on the earth were detected in the sun, while dark lines, not corresponding with the spectrum of any terrestrial substance, suggested the existence of solar elements hitherto unrecognised by the chemist. The spectra of the stars were found to vary, some showing the presence of hydrogen only, while others indicated the existence of constitutions more nearly approaching that of our sun.

The structure of the *nebulæ*, those vast, vague sources of luminosity, had long been a matter of speculation. Were they clusters of innumerable stars, so minute and so distant that the most powerful telescopes could not resolve them, or were they, indeed, as their name indicated, foregatherings of cloud-like, light-giving vapours? The question was settled as soon as the spectroscope was turned towards their light. A continuous gradation in properties was found between stars and *nebulæ*. Some *nebulæ* gave continuous spectra, indicating high density and pressure at the source of radiation, others gave bright lines on a dark background—the spectra, not of dense suns surrounded by cooler atmospheres, but of masses of glowing

vapour of great tenuity—the beginnings, perhaps, of suns and worlds yet to be.

Then came a pause in the progress of this new branch of knowledge. The spectroscope alone seemed to have told all it could to the human eye. A more sensitive instrument was needed to receive its messages, to intensify them, and to interpret them to the senses of mankind. It was not till photography was employed to record the results of spectrum analysis that the full power of the spectroscope was understood. Although previous attempts had been made by means of inferior processes to photograph the spectra of the sun and stars, the great success of the method dates from the application of the dry gelatine process by Sir William Huggins in 1876.

The photographic method has many advantages over direct visual observation. The sensitive plate can be exposed for a considerable length of time, and the effect of the light on it is cumulative. Excessively feeble light will, by prolonged action, produce a sensible impression on the photographic plate when it would be quite insensible to the eye, which has none of this power of gradually storing and intensifying its impressions. Again, the photograph will record ultra-violet radiation to which the nerves of the eye do not respond, and, in this way, it has revealed many invisible lines. Finally, the photograph forms a permanent record, to which reference can be made at any future time, and permits measurements, more accurate than those made by direct visual observation, to be obtained at leisure in the laboratory many

hours or days after the exposure. In several observatories, systematic records are kept of the state of the sky from night to night, and, more than once, when a new star has been detected, its previous history has been unfolded by reference to photographic plates exposed before the existence of the new star was suspected.

Two methods of obtaining spectra are known to the physicist, the instruments used being respectively the prism and the grating. The grating consist of a number of equidistant parallel scratches ruled on a reflecting surface of polished metal or on a transparent surface of glass. The scratches are very close together, many thousands of them being included in the space of an inch. When a wave of light falls on a metallic grating, the scratches refuse to reflect the light. The distances between the scratches are comparable with the minute wave-lengths of light, and thus different waves are differently treated by the grating. The component rays of a complex beam of light are separated from each other, and, if the source of light be a narrow slit, a number of parallel images are formed, and a spectrum is obtained. The deviation of any particular wave, such as the yellow sodium ray, will depend on the wave-length of the light, and, for the same grating, will depend on this wave-length alone. The spectral lines obtained will therefore have positions simply depending on the wave-length or period of vibration of the corresponding rays of light; in this differing from the similar lines given by the prism, which depend in position

on the qualities of the glass as well as on the periodic times of vibration of the different rays.

The sharpness of definition of a spectrum taken from a grating depends on the accuracy with which the scratches are ruled, and thus the perfection of the grating depends on our power of moving the scratching tool through exactly equal intervals between two scratches. To control the movement a perfect screw is required, and to Professor Rowland's improvement in the manufacture of screws in 1882, and to his idea of using them to rule gratings on concave metallic surfaces, is directly due the possibility of making adequate use of the resources of photography in the province of solar and stellar spectrum analysis. The arts and the sciences are closely related; an advance in one of them often leads to a corresponding advance in the other, and it is not always science that leads the way.

The concave grating banished the need for a lens to focus the rays after diffraction, and an image of the spectrum could now be obtained from the grating alone. Glass is opaque to much of the ultra-violet radiation, in which sunlight, at any rate, is very rich. Prismatic spectra and spectra taken with plane gratings and lenses do not show the ultra-violet lines. But, by the use of a concave grating and a reflecting telescope, the presence of glass becomes unnecessary, and investigation can be prolonged into the ultra-violet region till the increasing absorption of the earth's atmosphere for waves of shorter and shorter wave-length prevents the rays from reaching the surface of the ground.

Glass is opaque to the infra-red radiation also, and here again the advantages of the concave grating are manifest. The infra-red spectrum was examined, chiefly by Professor S. P. Langley of Washington, through the heating effects of its constituent rays. Professor Langley used an instrument called the bolometer, in which the heating effects of different parts of the spectrum, and consequently the position of the dark lines, are determined by measuring the change in electric resistance of a very thin strip of platinum exposed to the radiation. This form of platinum thermometer is extremely sensitive, and the spectrum of the sun has been mapped far below the limits within which the eye responds to the stimulus of light. And, in more recent years, the invention of new processes has carried photographic methods beyond the range of the eye at this end of the spectrum also.

Perhaps the most striking and interesting results given by the combination of camera and spectroscope are those obtained by the determination of the change in the refrangibility of light produced by relative motion of approach or retrocession of the source of light and the receiving station. Let us imagine that waves are proceeding from some source which remains at rest. A certain number of waves reach an observer in one second. If, however, the observer is approaching the source, it is evident that, as he is going to meet the waves, a greater number of them will reach him in one second than when he was at rest. Similarly, if the observer move away from the source, the

number of waves which reach him in a given time will be less than before. The same effects will be produced if the observer be stationary and the source of light move. Doppler's principle, as this change in periodic time is called, is well illustrated in the case of sound. Here the frequency of wave impulse on the ear determines the pitch of the note heard, and it is easy to detect a distinct flattening by a semitone or more, as the whistling engine of an express train passes the observer. The source of the waves of sound still vibrates with the same frequency, the change is only in the number of impulses reaching the observer per second.

The frequency with which waves of light are received by the optic nerve determines the colour perceived by the brain, and also the amount of refraction in passing through a prism. Thus the colour of a ray of a single definite wavelength, as well as its position in the prismatic spectrum, will be different from the normal value when the source of light and the observer are moving relatively to each other. An approach will result in a shifting towards the blue end of the spectrum owing to the increase in frequency; a recession will involve a reddening of the light, or a movement of the spectral lines towards the red end of the spectrum. Owing to the great velocity of light, the change will relatively be much less than in the case of sound. Light travels about 186,000 miles in one second, and, great though the speeds of the stars may be, they fall far short of such tremendous values. A velocity of eighteen miles a second, for example, the velocity of the earth in her orbit,

is but the ten-thousandth part of the velocity of light. This velocity of approach, then, would involve a change of the ten-thousandth part in the period of vibration of the incident light. The whole visible spectrum, from the red to the violet of the rainbow, includes a range of frequencies of about an octave, that is, the period of vibration of the extreme red is about double that of the extreme violet. A velocity equal to that of the earth, then, would involve a change in position of a spectral line of about the five-thousandth part of the total length of the spectrum. Many stars are approaching or receding from the earth at velocities higher than that which we have taken as an example, but still the changes in position to be measured are very small, and refined methods and great experimental skill are needed for accurate results.

The problem of determining the movement of a star travelling along the straight line joining it to the observer would, before this principle was discovered, have seemed one of the most hopeless problems which a cynical scientific sceptic could propose for solution to the physicist. Yet such problems are now solved daily, or rather nightly; solved, indeed, much more readily than they could be if the star were moving across the line of sight. In the latter case, even if a knowledge of the distance makes the determination possible, prolonged observations are needed, extending over months or years, till the movement becomes apparent at the distance of the earth. Many stars are so distant that no such cross movement could be

detected in any reasonable time. If, however, the star is moving towards or away from the earth, the spectroscope is turned towards it, and in the short time required to fix a photographic impression, develop and print the plate and measure the lines upon it, the velocity of the star can be determined.

Another application of the same principle has enabled us to demonstrate directly the rotation of the sun on its axis, and to separate those absorption lines in the spectrum of the sun's light which are due to the effect of the earth's atmosphere from the lines of true solar origin. One limb of the sun is, at any moment, approaching the earth, while the opposite limb is in like manner receding. By pointing a spectroscope first at one limb and then at the other, a shift of the spectral lines is seen ; and, from the amount of the displacement, the velocity of movement of the glowing gases which produce the lines of absorption can be calculated. Lines which are not shifted by this operation are clearly not of solar origin, and are consequently to be referred to absorption by the atmosphere of the earth.

Other problems in solar physics have been solved by the same method. The existence of sun-spots has long been known ; they were, indeed, familiar to the Chinese in very early times, and, in the middle of the nineteenth century, their periodic increase and decrease in a cycle of ten or eleven years was noted by Western observers, and a coincident period of terrestrial magnetic phenomena was established. The structure and properties of sun-spots were then seen to possess more than a local solar





FIG. 37.—C LINE IN THE SPECTRUM OF A SUN-SPOT
(*Professor Hale*).

interest, and their importance with regard to terrestrial meteorology became manifest. It has long been held that sun-spots were the seat of movements of gases on a gigantic scale in the solar atmosphere, and direct evidence of such storms is supplied by the spectroscope. Professor Hale gives a drawing of the spectrum of a sun-spot in the neighbourhood of the *C* line. This drawing is reproduced in Fig. 37. The slit of the spectroscope was directed to the sun's disc so as to include the area covered by the spot. The figure shows a small part of the spectrum, which extends from left to right across the paper. The faint horizontal dark line shows the effect of the sun-spot, from which much less light proceeds than from the rest of the sun's surface. Several faint Fraunhofer's lines cross the diagram vertically, and it will be seen that these lines are still dark lines in the sun-spot region. The sun-spot itself, then, must be the source of continuous radiation, from which definite rays are abstracted by cooler gases in higher regions, the process being identical with that going on in other parts of the sun. The heavy dark line crossing the figure from top to bottom is the *C* line to which reference has been made. It is much stronger and darker than any of the other lines shown. In the neighbourhood of the sun-spot, like the fainter lines, it still shows dark, but in its centre is a bright patch or reversal of the line. This intense luminosity indicates that, superposed on the layer of gas which absorbs the light, is a mass so hot that its radiation is even greater than the normal radiation from the sun's surface. The curious

hook-like appendage to the line, which begins as a fine point in the middle of the sun-spot absorption, and ends above by fusing with the *C* line, tells of an extraordinary outrush of cool hydrogen coming from the centre of the sun-spot area, and travelling outwards with a radial velocity of about one hundred and twenty miles a second. In its outward course it passes away from the sun-spot area, and finally comes to rest at a distance of thirty to forty thousand miles from its point of origin. Its absorption then of course coincides in spectral position with the normal *C* line.

Similar work, carried on in several observatories, has thrown much light on the movements of the prominences, which come into view at the edge of the sun's disc, and seem to be connected intimately with the spots. These enormous masses of glowing gas produce bright line spectra, and the displacement of the lines gives the movement in one plane, while direct visual observation gives that in a plane at right angles to the first. Thus the motion of the prominences can be specified completely. Their velocities are often as high as two or three hundred miles a second.

It seems unlikely that such high velocities can be the result of differences of gaseous pressure and the convection currents thus engendered. They are more probably to be explained by the local action of some explosive source of energy, by which matter is projected with great violence.

The application of Doppler's principle to

stellar movement has led to other results quite as remarkable as those already described. Our sun is a single system, but many of his fellows among the stars are accompanied by partners; the two existing in more or less close conjunction, and showing all the signs of a common origin. Some of these double stars can be examined by telescopic means, but the majority of them lie too close together to be separated thus. Often, too, one of the pair is not luminous, and therefore would never be visible. In this class are probably to be placed variable stars, such as the star known as Algol or β Persei, the light from which undergoes periodical fluctuations in intensity. The light keeps constant for the greater part of the cycle, and then diminishes for a short time before again rising to its normal value. This behaviour was long suspected to be due to the partial concealment of the star by a dark companion or satellite, and the surmise was confirmed by the spectroscope, which shows that the star is always receding from us before the loss of light and approaching after it. This result is exactly what we should expect on the eclipse theory, the dark companion being so nearly of the same size as the visible Algol that the joint motion is similar to that of two partners waltzing round each other rather than like the revolution of a small satellite round a large central body, which remains nearly stationary. In other cases, such as that of β Lyrae, the intensity of the light is never constant, but undergoes continual variation, accompanied by complicated changes in the spectrum. An explanation has been given by imagining two

ellipsoidal luminous bodies, which revolve round each other very near together, and send to the earth more light when they lie side by side than when one lies behind the other and to a certain extent obscures it.

It is evident that the double nature of such systems can be demonstrated by variations in luminosity only in the few cases where the motion is in such a plane that one of the partners is periodically interposed between the other and the earth. Only a limited number of Algol variables are known. When this eclipse does not happen, the dark companion could never be detected without the aid of the spectroscope. By continuous records of the spectra of many stars, however, periodic changes in the lines have been observed, and the times of the orbital movements determined. Binary systems have been discovered with periods varying from a few hours to many years. In some cases the spectral changes merely consist in periodic shiftings of the lines. Here we probably have a luminous body and a dark companion revolving round their common centre of gravity. In other cases, a periodic doubling of the lines indicates two bodies, both luminous, but too near together and too far from us to be separated by the telescope. The number of both classes seems to be considerable, and our visible universe must be studded pretty closely with dark stars, the existence of which is only to be detected when they are associated with some luminous companion.

Triple and multiple stars are also known. For instance, the Pole Star is a spectroscopic

binary with a period of four days, which revolves in a period of some twenty years round a third star invisible to us.

Passing from these questions to the problems of our own planetary system, we find the same principle applied to the examination of Saturn's rings. These remarkable structures, which in the telescope look like rings of continuous matter encircling the planet, were long a puzzle to the astronomer. Theory indicates that such rotating rings of continuous matter, whether solid or liquid, would be unstable, and would break up under the forces which must necessarily exist. The alternative hypothesis, that the rings consist of a swarm of tiny meteorites, each revolving round the planet in its own separate orbit, was elaborated mathematically by Clerk Maxwell, but no confirmation of this view was obtained till Keeler examined the rings with the spectroscope. He found that the inner parts of the rings revolved faster than the outer parts, in accordance with the requirements of the meteoritic hypothesis. If, on the other hand, the ring were solid, the outermost parts would possess the highest velocity, on the same principle by which the circumference of a fly-wheel moves faster than its inward parts.

While the knowledge of sun and stars delivered to us by spectrum analysis has been both extensive and striking, the interpretation of spectral phenomena has proved a much more complicated problem than was anticipated when Bunsen and Kirchhoff's great discovery first

placed the new method in the hands of investigators. The lines of the spectrum, whether bright or dark, were thought at first to be fixed and constant in position—that is, the modes of vibration of the atoms from which the light proceeded were imagined to be unaffected by any external circumstances. This supposed simplicity has been shown to be illusory. As we have seen, movement of the source and observer, although it may not alter the atomic vibrations, affects the number of them received in any time, and thus changes the refrangibility of the light they emit as it is received by the observer. But other variations, more fundamental in their origin, are known. Laboratory experiments have shown that the spectral lines alter their character with changes in the physical conditions of the experiments. It was thought that luminous gases evolved only bright, sharp lines. It is now found that the lines may be broadened and softened by an increase in the pressure or the density of the gas, while, in some cases, a simultaneous shift in position may be produced. An intense magnetic field has been shown by Zeeman to result in separation of single lines into two or more components, in this fulfilling the predictions of the electromagnetic theory of light, which suggests that some such connection is probable. The spectra of elements have long been known to depend on the temperature, the spectrum of the arc discharge often being different from that obtained by the use of a discontinuous spark, while neither correspond with the spectrum of the incandescent vapour existing in the flame of a

gas-burner. More recent experiments have shown that traces of impurities may modify the spectrum considerably, while, in some cases, the presence of one substance will completely mask the spectrum of another.

Again, when an atom is ionized, that is given an electric charge, some of its spectral lines are often found to become much more intense. These "enhanced" lines are very important in the interpretation of solar and stellar spectra.

The possibilities introduced by all these effects naturally complicate the interpretation of solar and stellar spectra. On the other hand, the very complications greatly increase the interest of the luminous messages, and the investigation of the connection between the external conditions and the nature of the spectra in the physical laboratory opens an almost limitless field to profitable research. Co-operation between the laboratory and the observatory doubtless will elucidate gradually the fascinating problems of the nature of the celestial bodies.

The spectra of various substances differ widely in complexity. Some consist of a few lines, some of very many. Iron, for instance, emits light of at least two thousand different wave-lengths. Of recent years, as explained on page 248, order has been introduced into our knowledge of complex spectra by the discovery that fairly simple relations hold between the wave-lengths, or rather the number of vibrations in a centimetre. Simple formulæ have been devised, which in a general way express the connection between the vibration number of one fundamental line and its companions, somewhat

as can be expressed the connection between a musical note and its overtones. Two or even three series of lines may exist, and two or three modifications of the formulæ are then needed to co-ordinate their vibration numbers. That such distinctions possess a physical significance was shown by experiments of Lenard, who found that the three series of sodium and lithium lines are separated in the flame of the electric arc, the outer shell of flame giving only the fundamental series, while, in the physical conditions appertaining to the inner flame, the second and third series become dominant.

We have already dealt in Chapter VIII. with the importance of these series of spectral lines in the problem of atomic structure, and shown how they enabled Bohr to explain the emission of radiation in finite units as required by Planck's quantum theory.

Some most interesting work relating to the sun was carried out by means of Professor Hale's method of photographing the sun itself and its prominences by the light corresponding with one definite spectral line. Two of the commonest elements present in the sun are hydrogen and calcium, and these elements are marked by the strong lines H and K respectively. The resultant photographs, then, show the distribution of hydrogen or calcium throughout the region investigated. The spectra of the prominences at the edge of the sun's disc consist of bright lines, while some of the dark absorption lines of the light from the surface of the sun possess bright centres, like those shown in Fig. 37, indicating



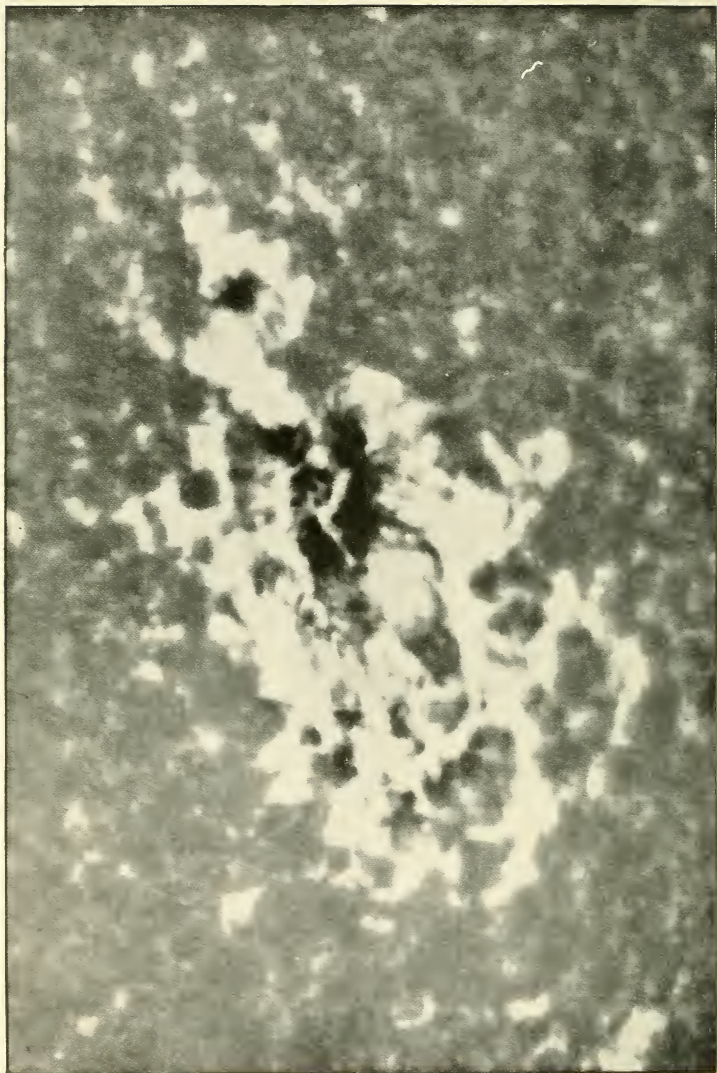


FIG. 38.—OCTOBER 9, 3^h. 30m. CALCIUM FLOCCULI, H₂ LEVEL.

the existence of masses of luminous vapour lying above the reversing layer. These bright central lines give sufficient light for the purpose we are now considering, and the resulting photographs show the distribution of glowing clouds of vapour in the higher regions of the solar atmosphere. Even the dark absorption lines are only dark by comparison with the brighter background, and thus new photographs can be taken with the darker sides of these reversed lines. The light then used comes from a deeper layer in the solar atmosphere, and as many as three calcium photographs have been taken in this way from a single line, showing the distribution of calcium at three different levels in the sun's envelope.

The method by which Professor Hale obtains these wonderful results consists in the employment of a spectro-helioscope possessing two slits. The solar light is focussed into an image by the telescope, passed through one of these slits, and thrown on to a prism or grating. The spectrum thus produced shows the usual lines, and the second slit is fixed so as to coincide with the line by the light of which the sun is to be photographed. The light coming through the second slit is thus monochromatic light—simple light of the particular kind desired. The first slit is made to travel slowly over the disc of the sun, and the second slit, by appropriate movements, is kept constantly in position to allow the particular line to fall upon it. In this way a complete picture of the calcium or hydrogen flames above the surface of the sun can be obtained.

One of the striking features of the photo-

graphs taken by this method consists in the well-marked differences in the distribution of hydrogen and calcium. The faculæ and prominences, which stud the solar disc, contain floating clouds of hydrogen, and other clouds of calcium, but these clouds are often separate from each other, and possess distinctive forms which are well shown in Figs. 38 and 39, and can at once be recognised by an accustomed observer as due to hydrogen or calcium respectively. Prominent objects on the sun, such as spots, often show clearly only in one of these two kinds of light, when they are faintly seen or are quite invisible by the other elemental ray. Vast clouds of calcium seem to arise from the neighbourhood of sun spots, obscuring the calcium light coming from the regions below, while at the same time the hydrogen light from those regions is able to make good its escape.

Most of the dark lines of the solar spectrum are probably due to elements known on the earth, some imperfect coincidences being attributed to the difference in physical conditions, which, as we now know, affect the character of the spectral lines. The bright lines of the outer luminous layer or chromosphere, and of its attendant prominences, were first detected during eclipses, though with modern instruments they can always be seen at the edge of the sun's disc. A brilliant unknown line in the yellow was in 1868 referred by Sir Norman Lockyer to a new element, to which was given the name of helium. In 1895 Sir William Ramsay detected the same spectrum by passing an electric spark



FIG. 39.—OCTOBER 9, 1^h. 04^m. HYDROGEN FLOCCULI.



through the gases evolved from a specimen of the mineral cleveite, and by this means isolated the gas helium, thus showing that the element, first discovered in the sun, was present also upon the earth. The complete spectrum of helium contains two sets of lines, one in the yellow and one in the green. In the laboratory these two sets are usually found together, though, by manipulating an electric discharge in helium, separation may be effected. In the light of the sun, too, the yellow line is sometimes found without the green. Other separations of the same kind between the constituents of the spectra of certain elements have also been observed, and have sometimes suggested the idea of atomic dissociation. Other explanations, however, seem, on the whole, more probable. Professor J. J. Thomson has shown that, when an electric discharge passes through rarified hydrogen, the red line becomes more intense near the positive and the green line near the negative electrode. This observation indicated a separation of hydrogen molecules into positive and negative parts giving different spectra. Taken in conjunction with more recent work on the enhancement of lines by ionization, it is very suggestive in relation to solar and stellar physics.

During total eclipse, a vast radiance surrounding the sun, known as the corona, springs into view. Spectroscopic examination shows that hydrogen, helium, and calcium, the main constituents of the chromosphere, are absent in the corona. The principal part of the light seems to be due to a brilliant green line, not produced by any terrestrial substance. The

hypothetical element emitting this light has been named coronium.

Although recent research has not yet led to a completely satisfactory conception of the general condition of the sun as a physical system, substantial progress in knowledge has nevertheless been made. The gigantic output of heat would be impossible for any solid globe, even if surrounded by a gaseous envelope. The external shell would cool too rapidly, unless a process of convection replaced the cooling gases on the surface by hotter ones from below. The temperature of the sun is above the critical points of most, at any rate, of known substances, and thus, although the pressures may be very high, liquids or solids are probably non-existent, except perhaps as clouds in the upper regions of the atmosphere. The best estimates of the temperature of the radiating part of the sun, based on the amount of solar heat received by the earth, corrected for absorption, agree in indicating a temperature of about 6000°C .

A fairly general consensus of opinion had been reached to the effect that the source of the energy required for the sun's continual output of heat was to be sought in the mutual gravitating condensation of his parts. A mass of gravitating gas may become actually hotter by radiation. As it loses heat, its parts approach, and the whole mass contracts. Two bodies attracting each other will, by their collision, set free energy which appears as heat, and the mutual approach of the gravitating parts is an effect of the same kind. The heat thus developed may be more

than enough to compensate for that lost by radiation. This reasoning was applied to the sun, and estimates of the sun's life as a useful radiating system were made by Lord Kelvin and others. But the past history of the sun was, on these calculations, far too short to admit of the periods required by the geologist and the biologist for the formation of the earth's crust and the evolution of species thereon.

It was thought at first that the phenomena of radio-activity would throw new light on this problem. If but two or three parts in a million of the sun's mass consist of radium, the present rate of heat emission would be maintained. The prevalence of helium suggests the occurrence of radio-active processes, during which, as we know, helium may be formed. But the balance of evidence seems against the idea that enough radio-active substance exists in the sun to explain his output of heat.

Indeed, no explanation yet suggested by known processes is adequate. We are forced to believe that some change, never seen in our laboratories, must be going on inside the sun. With the glimpses we have now had into the wonders of atomic structure such an idea need not surprise us. The temperature within the sun must be far higher than the mere 6000° of the radiating layer, and may be of the order of a million degrees. At such temperatures phenomena quite unknown to us may appear—the disintegration of atoms stable on earth, or possibly the direct conversion of electronic matter into radiant energy by collision. This is perhaps only vain speculation, put forward to

hide our ignorance, but it is certain that many changes quite beyond our range of terrestrial experiment may be going on in the flaming furnaces of the sun and stars.

The problem of the probable age of the earth is also surrounded with difficulty. The temperature of the earth rises as we pass underground, and, from the present temperature gradient, Lord Kelvin had calculated that about one hundred million years ago the earth was a molten mass. Although from the nature of the assumptions made in this calculation, little weight could be attached to the exact result obtained, the estimated age of the earth, as the home of organic life, was again too short for the requirements of geology and biology. But it is now known that radio-active matter in small quantities is very widely distributed throughout the earth and its atmosphere. Clay, for instance, yields a radio-active emanation in appreciable quantities, and potassium is slightly radio-active. Rutherford calculated that, if all the substance of the earth were as active as clay, the present distribution of temperature might be maintained by this cause alone. Such activity is unlikely, but the result shows, at all events, that the observed temperature gradient is not a safe guide when used as the sole means of estimating the age of the habitable globe.

The great advance in knowledge, gained by the study of the conduction of electricity through gases and the phenomena of radiation and radio-activity, cannot fail to exert a powerful influence on the future of astro-physics, and, in particular,

on our conceptions of the nature of solar processes. The leak of electricity from hot bodies, studied in the physical laboratory, shows that corpuscles or electrons must be emitted in enormous quantities by the substance of the sun and hot stars. The likelihood of the presence of radio-active matter, too, and of the ejection of other corpuscles, with the transcendent velocities impressed on them by a radio-active origin, must not be forgotten. Although the corpuscles, before they reached the surface of the earth, would be absorbed by its atmosphere—equivalent as that atmosphere is to a thickness of thirty inches of mercury—they might produce striking phenomena in the regions of the upper air. Perhaps on these lines is to be explained the appearance of the Aurora Borealis and kindred manifestations, while the luminosity of the solar corona may well have an electric origin.

One important application of photography to astronomy consists in the better estimation of stellar distances. Even the nearest fixed star is so far away from us that accurate measurement is difficult, while some stars are so inconceivably remote that all ordinary methods fail.

Nearer objects seem to move past more distant ones as we look at them from the window of a train; and, if some stars are nearer to the earth than others, they also should seem to move in one direction as the earth moves in the other. We should therefore expect to see the nearer stars shift over a background of more

distant stars as the earth travels in its orbit round the sun, and observation confirms this prediction. The first successful measurements were made telescopically in 1838, but much more accurate results can now be obtained by photography. If three photographs be taken of Sirius, for instance, at intervals of six months, and the distance of the image from those of three surrounding distant stars be measured with a micrometer, it will be found that Sirius moves. The small distance between his first position and that he occupies a year later gives his own proper motion compared with the earth and the very distant stars taken as "fixed." This motion is 1.32 seconds of arc in the year. Half this distance gives the position Sirius would occupy at the intermediate six months' interval if viewed from the same spot in space. The angle, 0.38 second, between this position and that actually observed is called the parallax; it shows the effect of changing the point of observation to the opposite side of the earth's orbit, that is by 185 million miles. From this it is clear that the distance of Sirius from the earth may be calculated. It proves to be about 50 million million miles, a distance it would take light 8.6 years to travel at its speed of 186,000 miles a second.

Beyond the range within which parallax is appreciable, stellar distances can only be estimated by indirect means. As examples we may cite the following methods.

The mean distance of a connected group of stars of given type may be estimated from their average magnitude, that is, their apparent

brightness, for on the average the fainter a star is the greater is its distance.

Certain stars show variations in the intensity of their light, with short periods ranging from a day to one or two months. A definite relation has been discovered between this period and the absolute brightness of the star in cases where the distances are known. Extending the same relation to a variable star at an unknown distance, an observation of the period gives its absolute brightness, which, compared with the apparent brightness, indicates the distance.

Globular clusters of stars of one type are found to possess approximately equal dimensions, so that the apparent diameter of the cluster enables an observer to make a guess at its distance.

The average velocity of the arms of spiral nebulae in the line of sight as measured spectroscopically is several hundred kilometres per second. This gives a rough value for the distance of those nebulae which show an angular movement of the arms across the line of sight, and a lower limit for the distance of those too far away for those movements to be measurable.

We can now appreciate the methods by means of which the dimensions of our stellar system have been estimated, and may pass to consider some of the results.

The mean diameter of the earth's orbit is 185.6 million miles. That of the orbit of Neptune, the outermost known planet, is about 5600 million miles, and this may be taken as the size of our solar system. Light would take 8.36 hours to travel across it.

Around our system lies a great abyss of space. The nearest known star—a faint speck called Proxima Centauri—is 24 million million miles or 4.1 light years away, more than four thousand times the stretch of Neptune's orbit. Then come three other stars before we reach Sirius at 8.6 light years.

A good eye unaided may see upwards of 5000 stars, while a large modern telescope (100-inch reflector) reveals a number estimated at 100 million. The number does not increase in proportion to the power of the telescope; hence we may conclude that our stellar universe is not infinite. The total number of stars is thought to be somewhere about 1500 million.

Some of this colossal number of stars are perhaps twenty thousand times as far away as Sirius, at a distance of some 170,000 light years. As we probe these appalling depths, we find gigantic spiral and spheroidal nebulae, and globular star-clusters. One of these clusters is distant from us about 200,000 light years, while another is so remote that the light by which we see it probably started a million years ago.

The milky way which stretches across the sky shows that the apparent distribution of stars is not uniform; the milky way contains more than we see in other directions. The stellar system seems to be roughly circular in one plane and flattened like a double convex lens with a diameter of at least 300,000 light years. Our sun lies somewhat to the north of the median plane, and about 60,000 light years from its centre. When looking at the

milky way, we are looking towards the rim of the lens, and therefore, owing to the greater depth, see more stars.

The appearance of temporary stars is a phenomenon which has been observed repeatedly in historical times. Hipparchus, Tycho Brahe, and Kepler, for instance, have recorded such manifestations. But the first case critically examined by modern photographic methods was that of Nova Aurigæ, a star discovered in February 1892, the origin and growth of which were traced by subsequent examinations of photographs taken in the previous December and January, and preserved as part of the systematic photographic log-book of the heavens now kept by astronomers. For three months the star's brightness lasted and then rapidly it decreased, till at the end of April the Nova was barely visible in the great refracting telescope of the Lick Observatory. Soon afterwards, however, a faint nebula appeared in its place, with a quite different kind of spectrum.

More completely studied were the striking phenomena of the second Nova Persei, first sighted at Edinburgh in February 1901. Its rise and decline were followed in many places, particularly by Father Sidgreaves at Stonyhurst, and by Professor Campbell at the Lick Observatory. It attained its maximum brightness about a day and a half after its detection, and then grew fainter in a fluctuating manner for about ten days. Finally, a nebula was seen to develop, which increased in visible dimensions at a prodigious rate—so fast, indeed, that the

most probable explanation supposes that the nebula was pre-existent but non-luminous, and was made visible by the flood of light released by the star. That light was reflected as it spread outwards from the centre in ever-widening spheres, and illuminated the scattered wisps of attenuated matter it encountered on its way through space. Calculating from this assumption, it is obviously possible to deduce the distance of the star, which proves to be such that light would take about three hundred years to reach our eyes. It would follow that the phenomena we studied in the last days of Queen Victoria represented changes that were occurring in the depths of space while Queen Elizabeth occupied the throne of England.

When examined spectroscopically, the light of all the temporary stars yet investigated shows one remarkable property. Bright lines, displaced towards the red, are accompanied by dark lines of similar origin displaced towards the violet. Doppler's principle would indicate that the source of these double lines was a double star, the bright lines coming from a gaseous system emitting a line spectrum, and the dark lines from a partner star in which absorption was predominant. But the difficulties of such a view seem insuperable. The requisite velocities are of the order of many hundreds of miles a second, and no sign of periodicity or even diminution appears in their values. At one time it was thought that the temporary blaze of light might be due to the shock of collision of two stars meeting in space; but the doubling of the spectral lines indicates a common constitution unlikely invariably to be

possessed by disconnected systems flying through space from distant sources. On the other hand, the opposite velocities, constant in amount, show that the two stars cannot be two members of the same group, colliding with each other as an effect of ill-directed mutual gravitation, which would lead to a decrease in velocity as the stars, after collision, receded from each other. The theory of collision has perforce been abandoned. No satisfactory hypothesis has yet been proposed in its place. Perhaps the one least open to objection is that which regards the luminosity as due to the passage of a star, possibly a dark one sometimes double, through the scattered matter constituting a nebula, in much the same way as a shooting star shines only during its transit through the earth's atmosphere.

Many years ago Clerk Maxwell showed theoretically that a stream of light, incident on a body, should produce a pressure in the direction of the advancing rays. Maxwell deduced the effect from the electro-magnetic theory of light, but it has since been shown by Larmor to be necessary on almost any wave theory. The undulations must possess energy, and, therefore, momentum. An absorbing body is gaining momentum, and therefore experiences a pressure in the direction of the incident beam. A reflecting body reflects the same momentum back again, and therefore is acted on by a double pressure. This result was first confirmed experimentally by Professor Lebedef, of Moscow. The difficulties to be overcome are best appreciated by the statement that when bright sunlight falls on a

reflecting surface, the pressure to be detected amounts to less than a milligram per square metre. For an absorbing surface such as lamp-black, the pressure is half as great as for a reflector, and it is the difference between these two effects that M. Lebedef has detected, the results of unequal heating and of molecular recoil being successfully eliminated. By another method the same pressure was also demonstrated by Nichols and Hull.

Owing to this pressure, two bodies radiating towards each other will experience a mutual repulsion, which, for small particles, may overcome the gravitational attraction. Even the attraction of the sun on a body may be neutralised if the body is of minute size, for the radiation effect depends on the area of surface, while the weight depends on the volume. As the size is diminished, the area decreases less rapidly than the volume, and, for microscopic particles less than 0.0001 millimetre in diameter, the radiative repulsion of the sun becomes greater than the gravitational attraction. An interesting application of this principle has explained the curious phenomena of comets' tails, which have long puzzled the ingenuity of astronomers. If, as is probable, a comet consists of a collection of meteorites, varying in size from small worlds to microscopic particles, on approaching the sun the large masses will follow the parabolic path *ABC* (Fig. 40), indicated by the ordinary gravitational theory. Particles of the particular size at which the radiative force just balances that due to gravity will pursue a path, *ADE*, in an undeviated course, for both the forces vary

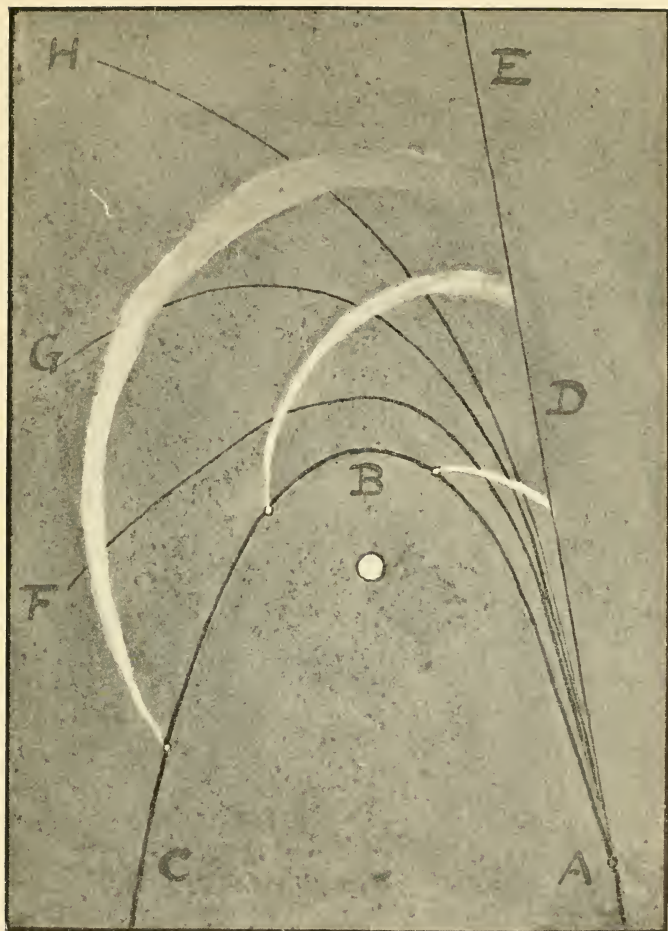


FIG. 40.—DIAGRAM TO EXPLAIN THE PHENOMENA OF
COMETS' TAILS.

inversely as the square of the distance, and will thus balance each other at all distances. Particles intermediate in size will follow intermediate paths, *AF*, *AG*, *AH*, etc., while the dust which suffers a resultant repulsion will fly away outside the path *ADE*. As the comet swings round the sun, the tail becomes expanded into the fan-like form commonly observed. The head of the comet goes on its way into the depths of space, having lost some of the smaller constituents of its tail, which are scattered throughout interplanetary regions.

Not only does the radiation from the sun cause a repulsion of small objects, but their radiation to each other will, as Professor Poynting has shown from the theory, lead to a mutual repulsion when the bodies are placed in a region of space where the effective temperature is lower than their own. Two meteorites at ordinary temperatures, say at 300° on the absolute scale, will in cold space repel each other with a force equal to their mutual gravitative attraction when their radii are about 3.4 centimetres, and, in the case of smaller bodies, the repulsion will overcome the gravitative effect. In this case, when the gravitational force is that between bodies of small mass, instead of that between some small body and the gigantic sun, a resultant repulsion is reached at much larger dimensions than those of the case formerly considered. It is evident that a swarm of meteorites of the right size might continue to revolve round a planet or sun without mutual forces and independently of each other. It is possible that this result

has some bearing on the problem of Saturn's rings.

A curious conclusion may be drawn from the theory of the radiation-force between small bodies. Unless the temperatures are the same, the force on one need not necessarily be equal to the force on the other: action and reaction it seems are not equal and opposite. The inconsistency is, of course, prevented if we remember that the momentum of the radiation must also be taken into account. In reality each body is emitting a stream of momentum which exists for a while in the medium. In the interaction between radiation and either body, Newton's laws may still hold. Constantly the energy and momentum of radiation seem to be exchanged with those of matter, and to be just as much physical realities.

If we neglect this last effect, there is no reason, in the case considered, why action and reaction should be equal and opposite. It is even possible to imagine the gravitation-pull and the radiation-push so adjusted that the accelerations become equal but in the same direction. The hotter body will then chase the colder body through space with constantly increasing velocity. A limit will, however, eventually be reached, for, owing to the Doppler principle, the waves in front of a moving body are crowded up, and those behind it lengthened out. The radiation-pressure in front is thus increased, and that behind diminished, so that the net result is a retardation which tends to check the motion. In the case of meteorites small but yet large enough for the gravitative pull to be

predominant, which are revolving round large bodies in orbits with high speeds, this retardation becomes important, and will eventually cause the meteorites to gravitate towards the centre. In this way it is possible that the sun may clear the neighbouring space of meteoritic dust, which would otherwise move round him in permanent orbits; and the earth would draw back to herself any particles shot out by volcanic eruptions, such as that of Krakatoa, when the velocities impressed may have been great enough to carry them beyond the atmosphere, and in the right direction to set them moving as satellites.

The theory of radiation also enables us to solve many other interesting problems connected with the solar system. By means of a thermodynamic proof it has been shown that the total radiation from a source should vary as the fourth power of the absolute temperature T , that is, as T^4 . By experimental investigation it is possible to establish a numerical relation, and, if R be the energy radiated per square centimetre per second by a full radiator such as lamp-black, the constant k in the theoretical equation $R = kT^4$ has been found by Kurlbaum to be about 5.32×10^{-5} erg.¹

Now we can calculate the total energy radiated from the sun per second by measuring the amount received at the surface of the earth, and estimating the amount lost by reflection and absorption by the atmosphere. These considerations lead directly to the effective tempera-

¹ The erg is the French unit of work or energy. About an erg of work is done when the thousandth part of a gram is raised through one centimetre.

ture of the radiating layer of the sun, which is thus estimated to be from 6200° to 7000° absolute. Professor Poynting prefers the lower value, which means about 6000° C.

A small body, isolated in space, will, when a steady state is reached, radiate as much heat as it absorbs. If it be shielded from the sun, it will attain a temperature which may be considered to be the effective temperature of space. From estimates of the amount of heat received from the stars, as compared with that received from the sun, Poynting calculates the effective temperature of space to be 10° absolute, or 263° C. below the freezing-point of water.

Similar principles give a basis for a determination of the temperatures of planets at any given distance from the sun. Assuming that all the heat absorbed is eventually radiated out again, and that about one-tenth of the incident heat is reflected, and making certain simplifying assumptions, the mean temperature of the surface of the earth is calculated as 290° absolute, or 17° C. The average temperature of the earth's surface is known to be about 60° F., or 16° C. The calculation is made on the assumption that the effective temperature of the sun is 6200° absolute, and its concordance with observation is the ground given by Poynting for preferring that value for the solar temperature.

This success in calculating the effective temperature of the earth lends weight to the values given by the same method for the temperatures of the other planets. Mercury and Venus, with orbits inside that of the earth, possess temperatures of 194° and 69° C.

respectively, while the outer planets, Mars and Neptune, fall as low as -38° and -221° . If there are, indeed, inhabitants on Mars, it seems that, according to terrestrial ideas, they must lead a very chilly existence.

We may now collect the various threads of thought we have followed, and weave them into a picture of the physical universe and its history.

Our stellar system seems to be a flattened lens-shaped galaxy of some 1500 million stars and nebulae, about 300,000 light years across its diameter. Though the stars vary greatly to us in brightness, that variation is chiefly an effect of distance or temperature, and the absolute masses of most stars range from about the same dimensions as those of our sun to some twenty times larger.

Interspersed with the stars, or perhaps in some cases beyond our stellar system, are nebulae, some irregular clouds of light, others of regular lens-like form, and again others with spiral arms, like an instantaneous photograph of a "Catharine's wheel" firework.

Laplace suggested that our sun and planets were formed from a nebula, and, in the three kinds of nebulae mentioned, modern science sees the development of star-worlds in the making. Mathematical analysis shows that a mass of nebulous matter of the size of our puny solar system would not develop as Laplace thought; its power of gravitation would not be enough, and its gaseous matter would diffuse into space and not condense. But the regular and spiral

nebulæ are on a far vaster scale—possibly a million times as great as the dimensions of Neptune's orbit. On this scale, gravitation would overcome the diffusive effect of gaseous pressure, and detached masses might become stars.

Mr Jeans has investigated mathematically the history of a mass of gravitating gas. It would, of course, form a sphere when at rest; but if, in the changes and chances of its nebulous life, it be set in rotation, the sphere will broaden out round the equator and flatten at the poles. While it is contracting under gravity, the angular momentum must keep constant, and therefore the speed of rotation must increase. The shape gets flatter and flatter, till the nebula resembles a double convex lens. And such, indeed, is the form of some of the nebulæ: one such is shown in Fig. 41.

At still greater speed, the lens-nebula must break up at the edge, and detach isolated globes of matter. This is clearly the meaning of the many spiral nebulæ, one of which is shown in Fig. 42. They are casting forth future stellar worlds. Each isolated globe is shown by calculation to be about equal in mass to that of the average star, and large enough to develop into a system such as our sun and his attendant planets.

Measurements of the actual movement of the arms of spiral nebulæ indicate that they are indeed matter flying out from the nucleus. The arms in Fig. 42, for example, are moving fast enough to complete a revolution in 45,000 years.



FIG. 41.—REGULAR SHAPED NEBULA (N.G.C. 5866) WITH BAND OF DARK MATTER ON EQUATOR.



FIG. 42.—SPIRAL NEBULA IN URSA MAJOR (M. 101).

Reproduced by kind permission from an article on "The Origin of the Solar System," by Dr J. H. Jeans in *Nature*, 1st March 1924.

The mathematical possibilities of development of these isolated masses, shows that they will not repeat the story of their parent. They are smaller beings, and instead of giving birth to a million new stars, or even a modest solar system, if left alone they will become covered with a gaseous atmosphere, or, if rotating rapidly enough, break up into two partners that spend their lives waltzing round each other, and are represented in nature by the countless host of binary stars.

No analogue of our solar system has been seen in the sky. Indeed, if one exists, it would be too small for the planets to be detected at the distance of even the nearest star. We have no model then by which its history may be illustrated, and can but turn to unconfirmed mathematical speculation.

Jeans has shown that the facts may be explained by the influence of a foreign body at an early stage of solar evolution. When the sun was a tenuous mass of nebulous substance, lately cast forth into space from the arms of some primordial spiral nebula, it may have passed near one of its brother stars or some other wandering body, which raised a tidal wave on its glowing surface. If the body came within a certain range, the tide would not subside as the body passed, but would surge upward, till finally the crest of the wave would fly off as a long streamer into space. This, being much denser than a mass detached by centrifugal action, might be held together by gravity, and would itself break up into masses which may have formed our family of planets.

Leaving this speculative account of the origin

of our own little, probably abnormal, system, let us now look at the more usual life of a star.

We have seen that a gaseous nebula will spin faster as it contracts under its own gravitation, but other changes will also occur. It radiates heat, but, owing to the fall of its outer layers towards the centre, more heat is developed from this loss of mechanical energy, and the nebula or star grows hotter. As the temperature rises, radiation pressure reinforces gaseous pressure, and these two causes oppose gravitation. All the time the star is growing denser, and the possibility of further shrinkage, and therefore of heat development, less. Hence a maximum temperature must be reached, after which the star, having passed middle age, gets slowly older and colder.

These mathematical predictions are well supported by astronomical evidence. The earliest classification of stars was made on a scale of apparent brightness. Hipparchus chose about twenty of the brightest stars as of the first magnitude, and classed the faintest stars he could see as of the sixth magnitude. In the modern form of this grouping, a star of one magnitude gives 2.5 times as much light as one of the next lower magnitude, and a difference from the first magnitude to the sixth corresponds to a ratio in brightness of a hundred to one.

When photography was applied to this problem, a new scale of brightness was obtained, for the ordinary plate is more sensitive than the eye to blue light and less sensitive to red. Hence the number found by subtracting the visual magnitude from the photographic is a

criterion of the colour of the star and is called its colour index.

The next method of grouping is by means of stellar spectra. This was first done by Father Secchi, who found that the spectra could be grouped in four broad classes, agreeing closely with a classification according to colour, from white to dark red.

This grouping has been superseded by a great catalogue of about a quarter of a million stellar spectra made at Harvard Observatory. The spectra are found to fall in a continuous series, the various main groups being denoted by the letters O B A F G K M N R, and each of these groups being subdivided. The spectra range from a faint continuous background with bright lines of class O, through bright spectra with helium and hydrogen dark lines, and then through lines of metals such as calcium to the complex spectra of type G, which includes that of our sun. In type K the hydrogen lines get fainter and the blue end of the spectrum becomes less intense; then in groups M and N are seen absorption bands due to titanium oxide and carbon compounds. These latter stars are red in colour.

Now as we heat a body, it first glows with a deep red light and then becomes yellow and finally white hot. The spectrum shows that, in accordance with this common observation, for a black body which is a perfect radiator, the wave-lengths which give the maximum energy of radiation are shorter the higher be the temperature. Hence, by measuring the distribution of intensity in the spectrum of a star, the

effective temperature may be estimated. It proves to range from about $25,000^{\circ}\text{C.}$ for the hottest stars of type O, to about 2300°C. for stars classed as R. These figures, of course, refer to the radiating layer towards the outside of the star; within, the temperature must be much higher, mounting perhaps to some millions of degrees.

The spectrum of a star must not be expected to show lines corresponding to all the elements which that star contains. Experiment in our laboratories, as we have seen, shows that electric ionization greatly increases the intensity of the spectral lines of the element ionized, and it will be chiefly these "enhanced" lines that mark a stellar spectrum. Ionization depends on temperature as well as on the nature of the elements present—another reason why a classification by spectra is also a classification by temperature.

If the distance of a star be known, the apparent magnitude may be used to calculate the absolute magnitude, that is, the brightness the star would show if removed to a standard distance.

When stars in the different spectral types O B A F G K M N R are examined for absolute magnitude, a remarkable result becomes apparent. While the brightness of the very hot stars in class B is of the same order throughout, ranging only from about 40 to 1600 times the brightness of our sun, the cooler stars such as those of type M, fall into two well-marked groups, one with luminosities approaching those of the hottest stars, and the other with a brightness of the

order if only the one ten-thousandth part of that of the others.

Professor H. N. Russell, who discovered these two types, calls them "giant stars" and "dwarf stars" respectively. They illustrate in a marvellous way the mathematical theory of stellar evolution. Beginning as a diffuse nebulous mass, our new-born star, as we saw on page 302, grows hotter by contraction, and passes up the scale of spectral types from R through M, and if it be large enough, reaches the class B or even O. All through these ages, it is radiating energy fiercely, and shining afar. It is a "giant" star. But a maximum temperature is reached, perhaps in the types A or B, and thereafter, the density having already become great, the heat gained by further contraction is less than that lost by radiation. The temperature of the outer radiating layers drops back through its old range, and so the light of the star also passes back along the series of spectral types from B or A towards M, N, and R, though certain differences between ascending and descending spectra have been recognised. But now the star is no longer inwardly a gigantic mass of turbulent vapour ever growing hotter, but a much smaller, denser body, with a colder, calmer future before it. The star has become a "dwarf." As it declines in vigour, its light becomes redder, like that of a cooling iron bar, and finally it vanishes out of sight, to make its existence known to us, if at all, by passing periodically as a dark body round a still luminous partner.

When any branch of learning first finds itself

in a position to use the methods and accumulated experience of another science, a period of striking discoveries may confidently be anticipated. Thus it was that Newton applied to the phenomena of the heavens the mechanical knowledge of previous ages, and his law of gravity revealed a harmony of the spheres. When it was found that the generalisations of thermodynamics and of electrical science could be used in chemical problems, a new world opened before the investigator. So it is with the transfer of physical methods and data to the problems of astro-physics. The first-fruits of this harvest of knowledge have already proved of momentous import, and in the combination of physics and astronomy the present labourers and those that come after them may hope to find one of the most fertile unions in the whole realm of Natural Philosophy.

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